9. Special-Application Requirements

9.1 INTRODUCTION

Preceding chapters of this handbook have discussed general requirements of high-efficiency air cleaning systems as they pertain to the more usual applications. This chapter discusses special requirements that may have to be considered for certain applications, including remote handling of filters and/or adsorbers, shielding, design to resist natural phenomena such as a tornado or earthquake, provision for fire protection, high-capacity sand and deep-bed glass fiber filters, ESF systems, and considerations for radiochemical plant ventilation and off-gas systems.

9.2 REMOTE MAINTENANCE

In some radiochemical, fuel-reprocessing, and reactor postaccident cleanup applications, radiation levels may be so high that direct access and contact maintenance will be impossible. Therefore, the servicing and replacement of filter and adsorber cells must be accomplished by remote methods. Remotely maintainable systems must achieve the same objectives of high collection efficiency and reliability as other installations, but design and construction are complicated by the necessity for radiation shielding and the need to manipulate clamping devices and handle components indirectly and from a distance. Federal regulations specify a maximum exposure to personnel in restricted areas of 3 rems to the whole body and 18.75 rems to the hands and forearms in any calendar quarter.[1] If radiation levels in filters or adsorbers approach or could reach these levels, contact maintenance may be prohibited, and consideration must be given to remote procedures.

Radiation exposure can be minimized by limiting the time of exposure, by attenuating the radiation by means of shielding, and by reducing the intensity of exposure by keeping a safe distance from the source (intensity follows the inverse square law). A practice in some low to moderate hazard systems has been to limit the time of exposure by sending workmen into contaminated housings in relays. Such procedures run the risk of exhausting the permissible radiation allowance of personnel so that their availability for work in other contaminated areas of the plant is limited. Even in borderline cases, it is advisable to consider remote maintenance.

Specific recommendations on how remote maintenance should be accomplished cannot be made. Only a few truly remote systems have been built to date, and approaches to the problem have varied widely. The installations described below are representative and illustrate some of the problems and factors that must be given consideration in designing such systems.

9.2.1 General Considerations

Clamping devices and components (filters, adsorber cells) of remotely maintained systems are handled by special extended-reach tools; electromechanical manipulators; solenoid-, pneumatically-, or hydraulically-actuated devices; cranes; or other indirect means. In some systems (Figs. 9.1 and 9.2 and Figs. 9.5 through 9.14), filters are installed on a removable mounting frame that is replaced as a complete assembly by means of a crane. In three of the systems illustrated, the entire housing is replaced. In most cases, housings will be enclosed in concrete vaults or pits, with heavy concrete plugs to seal access ports. Designers must recognize that workmen do not have the close control over movement of tools, equipment, and components that they do in direct-access contact-maintenance systems. Careful attention must be paid to filter (adsorber) withdrawal and handling space, and, if alignment guides are not provided, access ports must be generously sized to permit the easy passage of components when handled by crane or manipulator. When filters and adsorbers are installed on a removable frame which is, in turn, sealed into a housing, heavier construction is needed

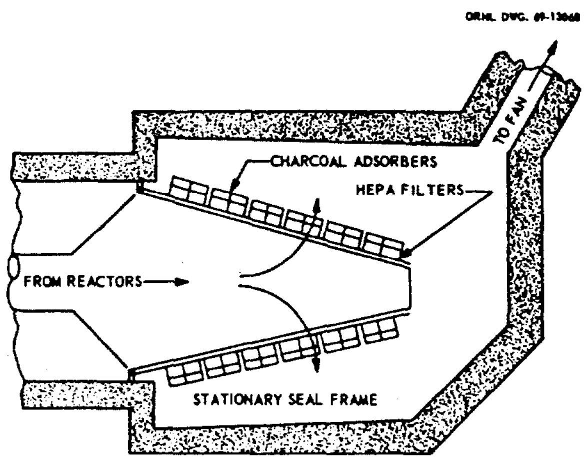


Fig. 9.1. Plan view of the bypass filter pit at Brookhaven National Laboratory. Each stack of eight HEPA filters and charcoal adsorbers is clamped to a removable mounting frame that in turn is clamped to the stationary seal frame, as shown in Fig. 9.2.

to prevent damage to the frame and to the sealing surfaces of the housing from inadvertent bumping of the removable frame against the stationary frame or the sides of the access port. Recommendations for the design and construction of concrete vaults and pits are given in ANSI N101.6, *Concrete Radiation Shields*.[2] This standard includes recommendations for roof and penetration plug design, clearances, and tolerances.

In some systems, the contaminated filter or assembly of filters is withdrawn into a special cask or enclosure to permit safe transport through occupied areas of the building or plant to a disposal area. Building openings, areaways between buildings, and ground clearances for power lines and other utilities must be adequate to permit easy passage of the heavy shielded cask and the truck or trailer on which it is hauled. Underground pipelines along the route may have to be reinforced to prevent crushing under the load.

For hot cells, caves, and canyons, it is recommended that first-stage HEPA filters be installed at the duct opening and in a manner whereby they can be replaced by withdrawal into the contained space. In most cases this will permit contact maintenance on the second-stage filters installed downstream in the duct. Provision must be made for access to the first-stage filters and for withdrawing them into the cell without interfering with process or experimental equipment in the cell.

It is often possible to design systems for both contact and remote maintenance, that is, to provide for contact maintenance when radiation levels are low and for remote access when radiation levels become high. This approach is particularly appropriate for reactor postaccident cleanup systems where radiation levels during normal operating conditions are well within personnel tolerances, but may be prohibitively high following an accident. The filters of such a semiremote system are held to the mounting frame in the conventional manner, but the mounting frame can be removed as a whole or as a segment, if necessary. Construction of the removable mounting frame and the stationary frame to which it seals must be precise to ensure a reliable and leaktight seal, and construction of both must be heavier than required for contact maintenance systems to withstand the rough treatment that they might receive during a remote filter or adsorber change.

Each step of a remote filter (adsorber) change, from initial dressing up of personnel in protective clothing to final disposal of contaminated components and decontamination of equipment and the area, must be carefully planned before system design is frozen. Overlooking any detail may complicate operations in the field and result in unduly high labor costs, spread of contamination, injury to personnel, or overexposure. Clearances, temporary storage of new and dirty components, equipment space, access to and from the area, decontamination procedures, radiation monitoring, utilities, and handling facilities must all be carefully examined. It is often desirable to build a model or full-size mock-up of the proposed installation to ensure that all factors have been considered. The mock-up or model can later be used for crew training.

9.2.2 Brookhaven Reactor Bypass Filter System

This system[3] is installed in an unlined concrete pit (Fig. 9.1) which has removable concrete shielding blocks in the ceiling to provide access to the filters and adsorber cells. These components are installed on 12 removable multifilter mounting frames which, in turn, are sealed to stationary frames in the pit, as shown in Fig. 9.2. To change filters or adsorbers remotely, the shielding blocks over the stationary sealing frames are removed, the latches that clamp the removable frames to the stationary frames are released from above by means of extended-reach tools, and the removable frames are hoisted out by crane.

Radiation levels are low enough under normal operating conditions to permit direct access for filter

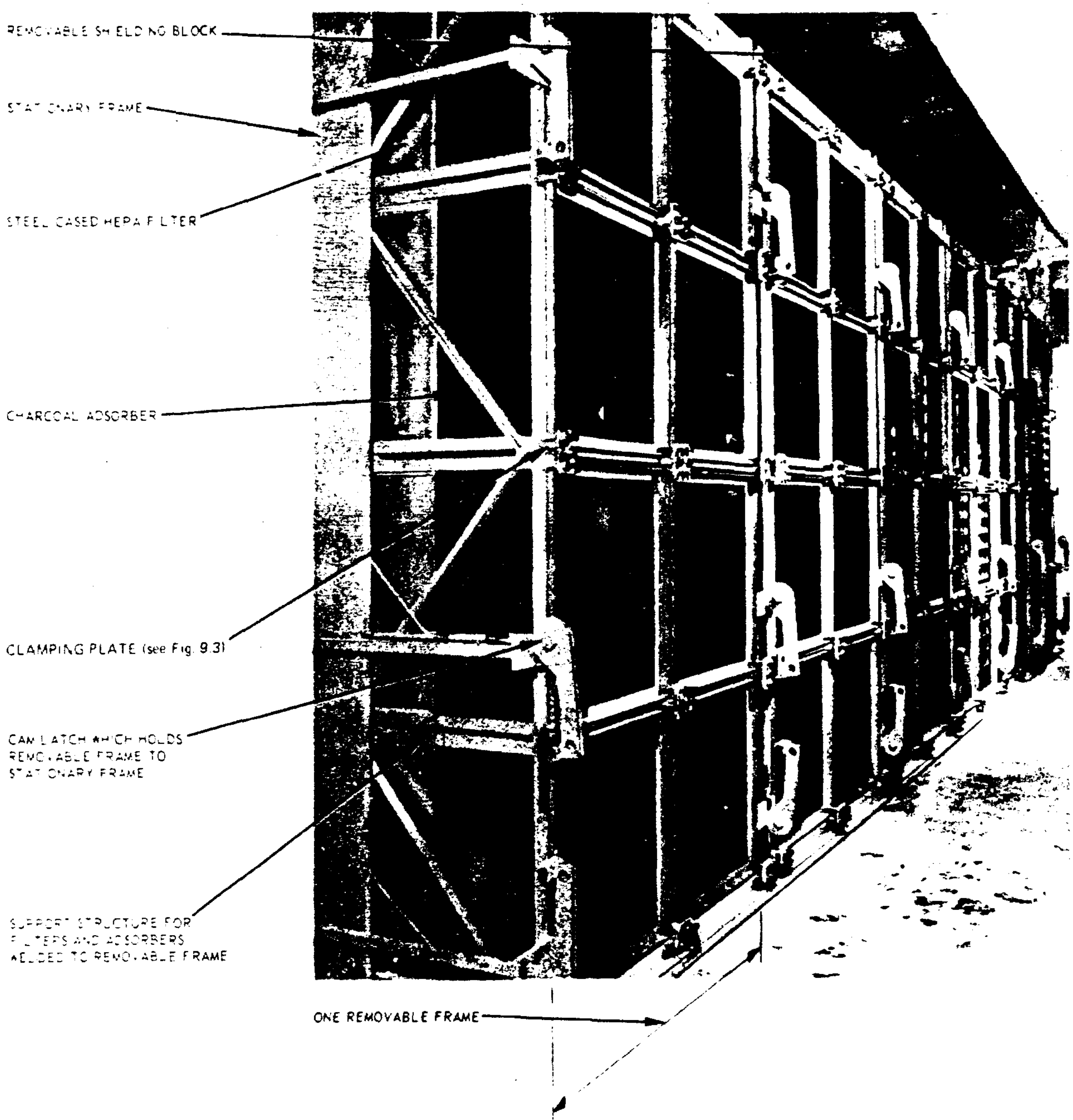


Fig. 9.2. General view of filter bank, Brookhaven bypass filter pit. Cam latches can be released from outside the pit by means of extended-reach tools, enabling the frame assembly to be hoisted out by crane through an opening in the ceiling. Note undesirable back-to-back installation of filters and type I adsorber cells. Courtesy Brookhaven National Laboratory.

and adsorber replacement. Figure 9.3 illustrates one of the clamping-plate assemblies that hold these components to the removable mounting frames. The plate is bolted to the frame after the filters and adsorbers have been positioned in the support structures; the clamping screws are then tightened on the pressure-distribution rings. This type of clamping permits the readjustment of individual filters or adsorbers after installation, but does not permit replacement without upsetting the seals of surrounding components. The practice of clamping adsorber cells directly to the faces of the HEPA filters is generally not recommended; however, it does represent one of the compromises sometimes made in a remotely maintainable system. The coupling of filters and adsorbers complicates contact maintenance

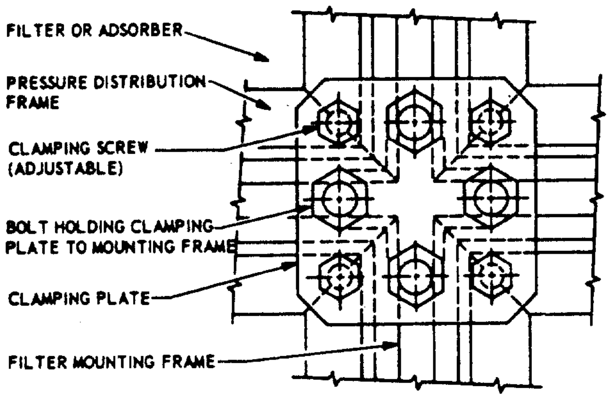


Fig. 9.3. Clamping plate assembly, Brookhaven bypass filter pit. Clamping pressure on individual filters is adjustable, but entire assembly must be removed to replace a filter.

because it is necessary to replace both filters and adsorbers at the same time and to remove the adsorber cells to get to the filters.

9.2.3 Hanford Reactor Filter System

The Hanford reactor air cleaning filters[4] are installed in underground pits having the configuration shown in Fig. 9.4. Each compartment contains 36 moisture separators, 36 HEPA filters, and 36 pleated-bed adsorber cells installed on removable frames, as shown in Fig. 9.5. These components are changed by replacing the removable frames, as shown in Figs. 9.5 through 9.14, which illustrate some of the problems of handling, space, and contamination control inherent in remotely maintainable systems. Radiation levels during the HEPA-filter change shown were not high enough to prevent direct access or to require burial of the contaminated mounting frame and its parts. The operation was constantly monitored (Fig. 9.13), and contaminated items were protected with plastic bags (Figs. 9.9 and 9.10) to minimize the spread of radioactive dust that might fall from the contaminated filters or frame during handling and storage. If this operation had been done after a major reactor accident, personnel would not have been allowed so close to the contaminated housing or filters, and the entire frame assembly, including filters, might have had to be disposed of as radioactive solid waste. The size of the mounting frame, approximately 22 × 9 × 3 ft, is indicative of the disposal problems that could be encountered.

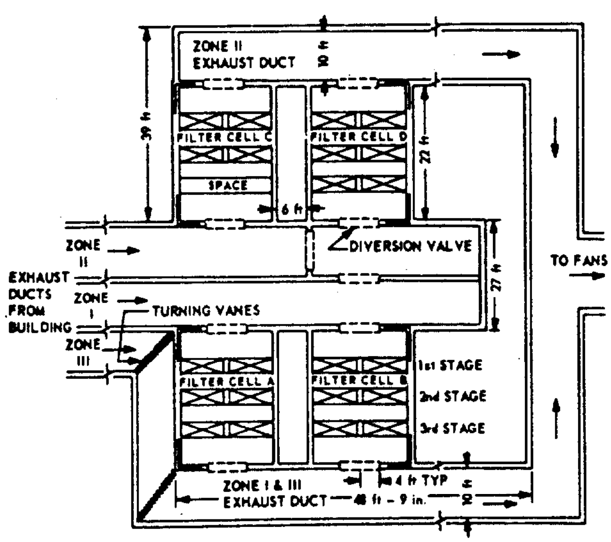


Fig. 9.4. Plan view of Hanford reactor filter system. First stage contains moisture separators, second stage contains HEPA filters, third stage (cells A, B, and D) contains pleated-bed charcoal adsorbers. Cells A, B, and C are on-line, cell D is normally held in standby. Courtesy ERDA, Richland Operations Office.

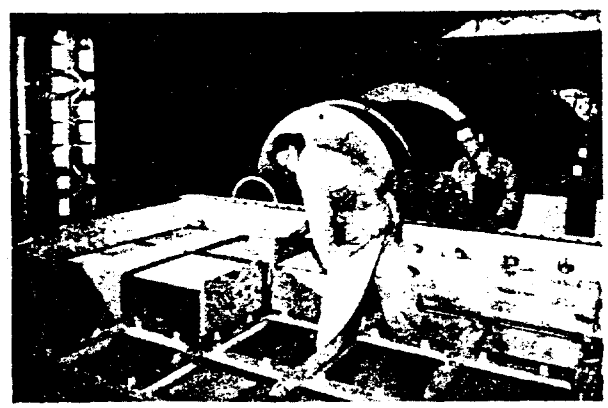


Fig. 9.5. Remote filter change, Hanford production reactors. Loading new filters in removable mounting frame. Courtesy ERDA, Richland Operations Office.

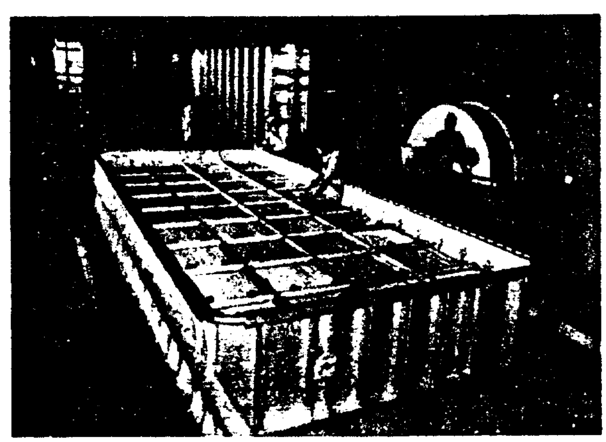


Fig. 9.6. Remote filter change, Hanford production reactors. Filter installation complete. Courtesy ERDA, Richland Operations Office.

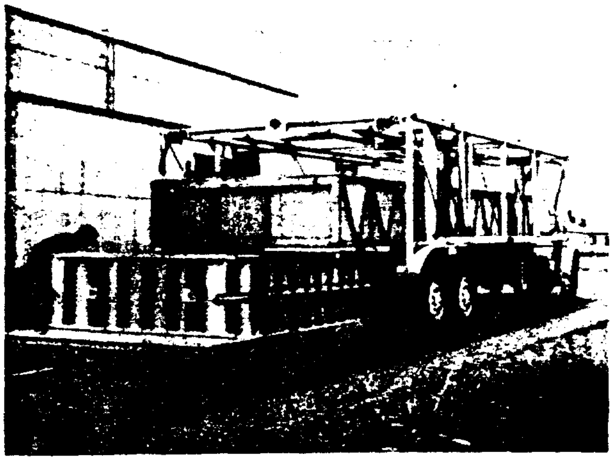


Fig. 9.7. Remote filter change, Hanford production reactors. Delivering new frame assembly to installation site. Note special trailer, protective box, and storage space required. Courtesy ERDA, Richland Operations Office.

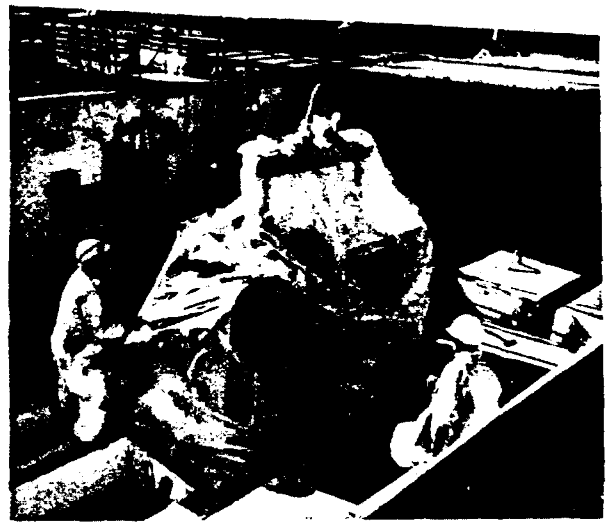


Fig. 9.9. Remote filter change, Hanford production reactors. Withdrawing contaminated frame assembly into plastic contamination shield. Courtesy ERDA, Richland Operations Office.

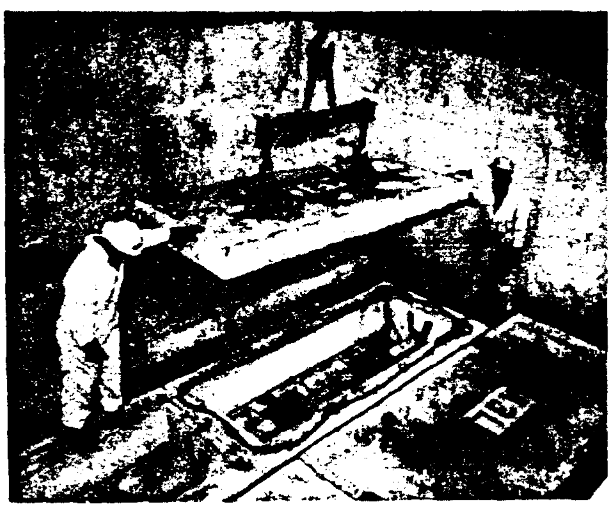


Fig. 9.8. Remote filter change, Hanford production reactors. Removing shielding blocks from filter pit. Note inflatable seal between block and pit. Courtesy ERDA, Richland Operations Office.

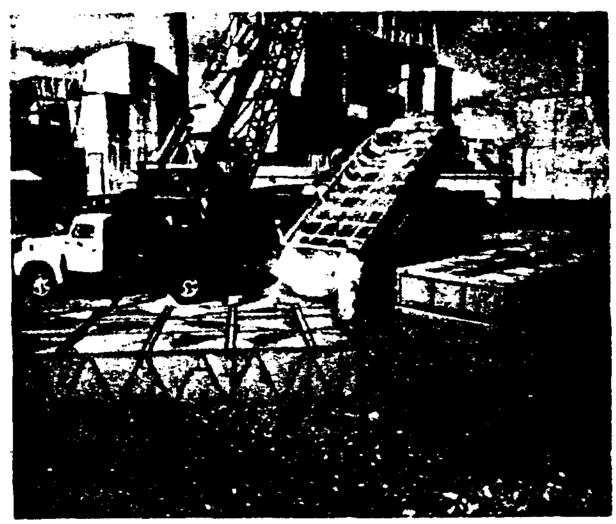


Fig. 9.10. Remote filter change, Hanford production reactors. Temporary storage of contaminated frame assembly. Note space required. Courtesy ERDA, Richland Operations Office.

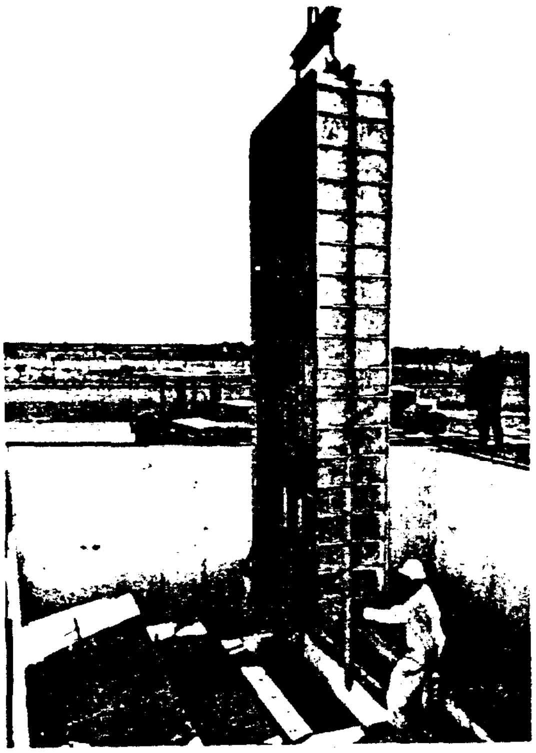


Fig. 9.11. Remote filter change, Hanford production reactor. Positioning new frame assembly over filter pit opening. Note alignment pins. Courtesy ERDA, Richland Operations Office.

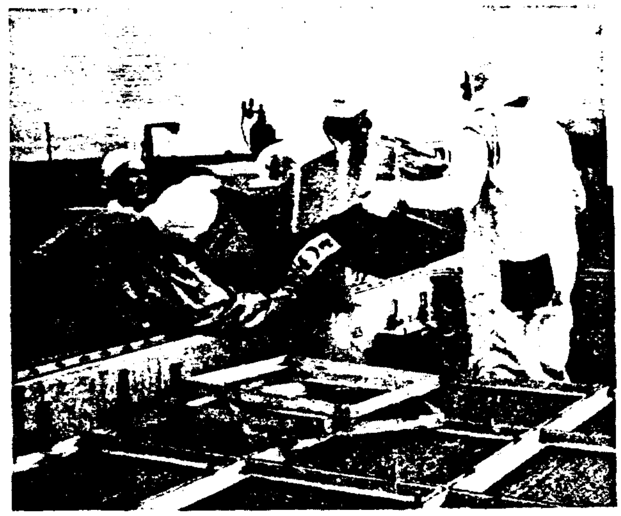


Fig. 9.13. Remote filter change, Hanford production reactor. Disassembling used frame assembly. Note radiation monitoring, protective clothing. Courtesy ERDA, Richland Operations Office.

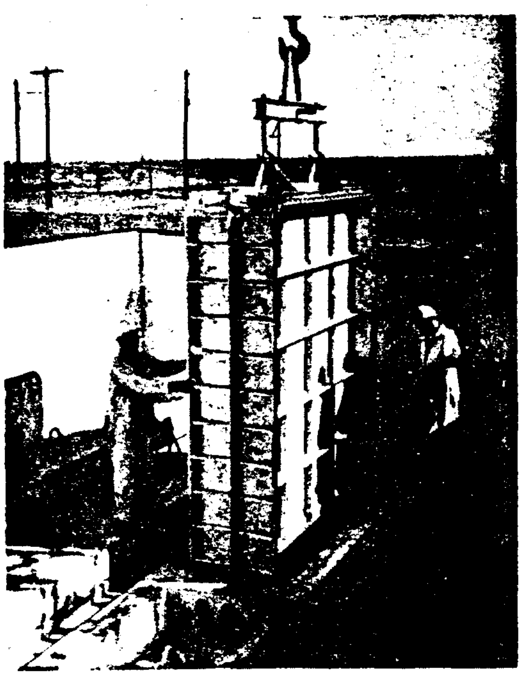


Fig. 9.12. Remote filter change, Hanford production reactor. Lowering new frame assembly into pit. Note lifting assembly. Courtesy ERDA, Richland Operations Office.

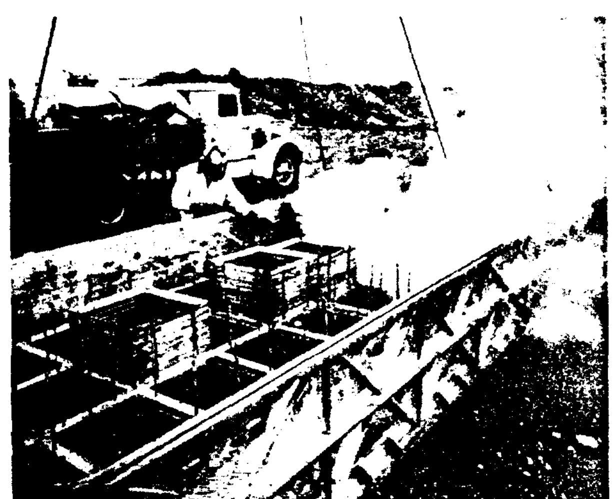


Fig. 9.14. Remote filter change, Hanford production reactor. Cleaning used frame assembly. Note portable steam supply, protective clothing. This type of cleaning is permissible only when contamination levels are very low. Had the frame been badly contaminated, it would probably have had to be buried. Courtesy ERDA, Richland Operations Office.

9.2.4 HFIR Filter System

Figure 9.15 shows the remotely maintained underground air cleaning system of the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, Oak Ridge, Tennessee.[5] The small system on the right handles normal off-gas from the reactor and other point sources, and the larger system on the left treats the exhausted air from the continuously vented containment building. Two "filter trains" of each system are on-line at all times, with the third in standby. Each train consists of a prefilter, a HEPA filter, two pleated-bed adsorption stages, and a final HEPA-filter stage. Components in the 1000-cfm nominal capacity off-gas system are individual 1000-cfm units. Components in the building ventilation system are banded together in stacks of three with stainless steel strapping, as shown in Fig. 9.16, using a commercially available banding device. There are four sealing faces in each of the stationary frames in each pit; a stack of filters (adsorber cells) is installed by forcing it against the stationary frame by means of the removable wedge installed between the back side of the filter stack and the stationary wedge. Bottoming lugs on the stationary wedge prevent overstressing the filter cases. The stacks of filters and the removable wedges are installed and removed by means of a crane.

This type of clamping system calls for a high degree of accuracy in installation and adherence to very close fabrication tolerances. The stationary frame is made from square tubing and the wedges from $^3/_8$-in. plate. The flatness and parallelism of the stationary frame and seating surfaces of the wedges must be within $\pm^1/_{16}$ in. in 6 ft and preferably closer. The spacing between the sealing face of the stationary frame and the stationary wedge is critical and must be maintained within $\pm^1/_{32}$ in. of specified values. Such tolerances are difficult to maintain during construction, and the mounting frame or wedge can be knocked out of tolerance by careless handling during a filter (adsorber) change.

9.2.5 Savannah River Reactor Filter System

This system[6] differs from the preceding systems in that the entire filter house is removed and disposed of if it becomes contaminated. Each housing contains a bank of 20 moisture separators, 32 HEPA filters, and 32 pleated-bed carbon-filled adsorber cells. The complete system consists of five once-through housings, four normally on-line and one in standby. The housings are mounted on railroad trucks that run on rails to the edge of the roof of the reactor building. Isolation dampers are installed in the building, as shown in Fig. 9.17, and the housing (Fig. 9.18) is

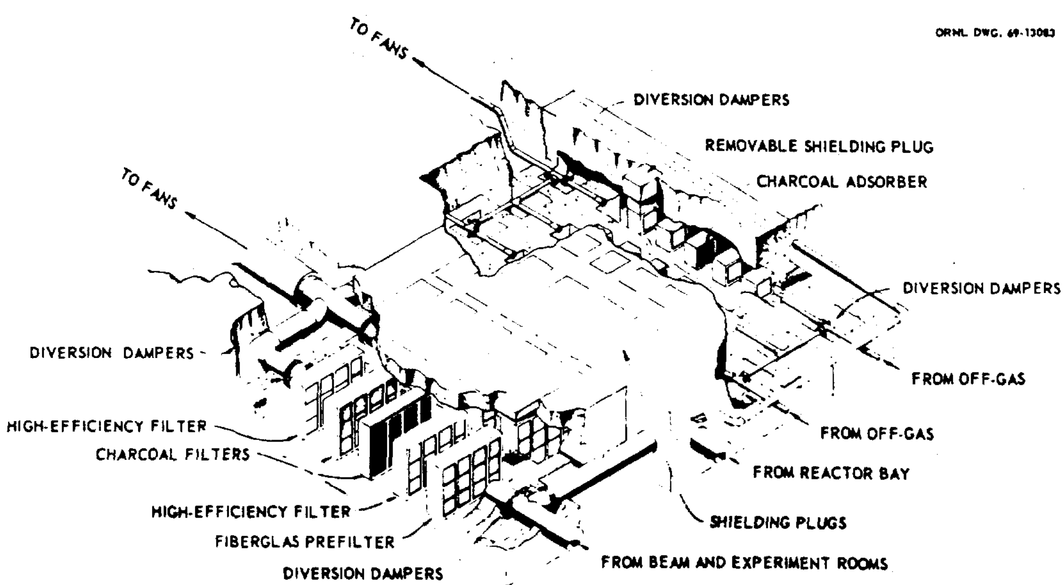


Fig. 9.15. General arrangement of underground filter pits at High Flux Isotope Reactor, Oak Ridge National Laboratory. Demisters (not shown) are located in the ducts leading to the pits. Courtesy Oak Ridge National Laboratory.

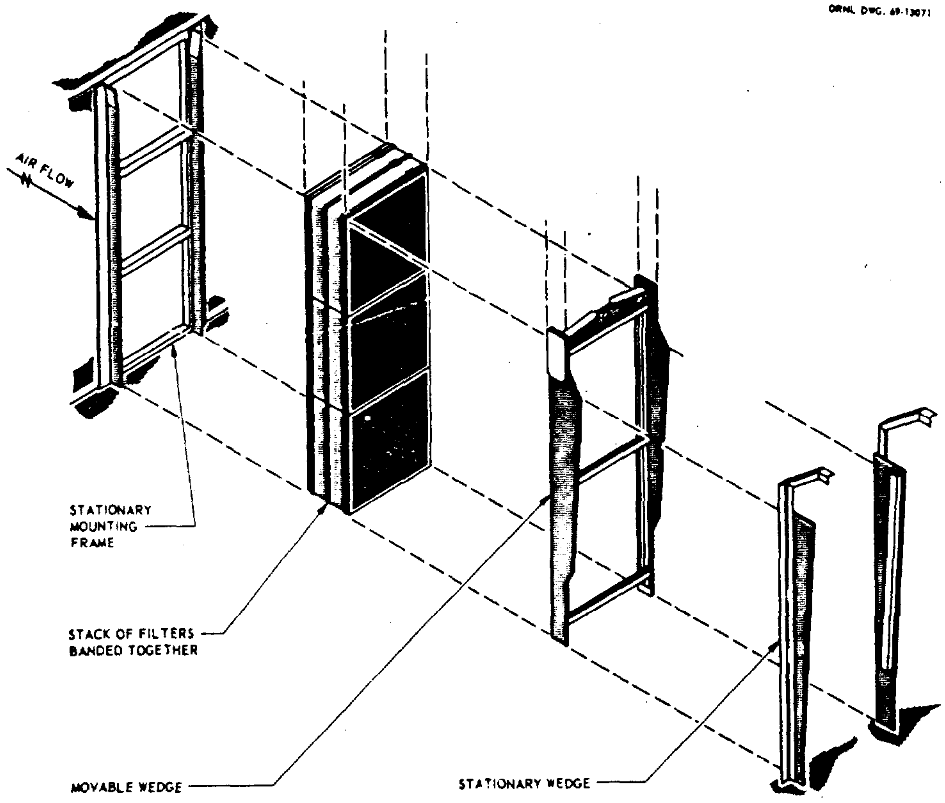


Fig. 9.16. Exploded view of filter clamping method, High Flux Isotope Reactor filter system. Actual distance from face of stationary mounting frame to stationary wedge is approximately 15 in.

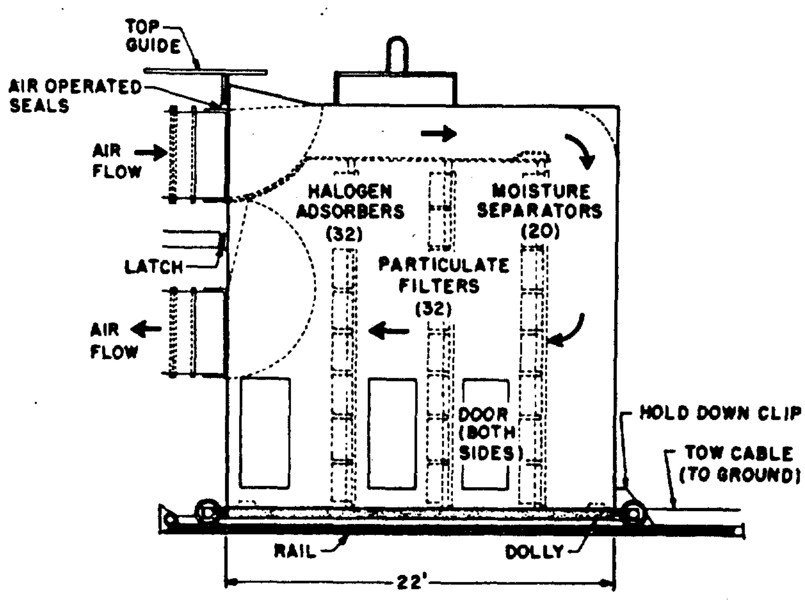


Fig. 9.17. Section through Savannah River Reactor confinement system filter compartment, as installed on roof of reactor building. From J. W. Little, Jr., and J. W. Joseph, Jr., "Confinement of Airborne Activity from Melted Antimony Slugs," *Proc. 12th AEC Air Clean. Conf.*, USAEC Report CONF-720823, January 1973.

sealed to the building by means of an inflatable pneumatic seal. To remove a housing, it is released and drawn away from the building by means of controls installed outside of the building at ground level. It is then lifted by crane and lowered to a railroad siding or truck trailer on the ground. Isolation valves and clamps holding the housing to the building are controlled either from the reactor control room or from the local station outside of the building.

Radiation levels are low enough under normal operating conditions to permit contact maintenance. Access doors in the opposite side of the housing shown in Fig. 9.18 permit entry to each chamber. Components are clamped to the mounting frames by a conventional nut-and-bolt arrangement. In November 1970, when an irradiated antimony source rod overheated while suspended in air in one of the reactors, about 6250 Ci was carried by the building ventilation air to the confinement filters. Of this amount, only 3 mCi escaped from the building exhaust stack, indicating a 99.999% capture efficiency for the filters.[7] The four units (housings) on-line at the time of the accident were continued in service

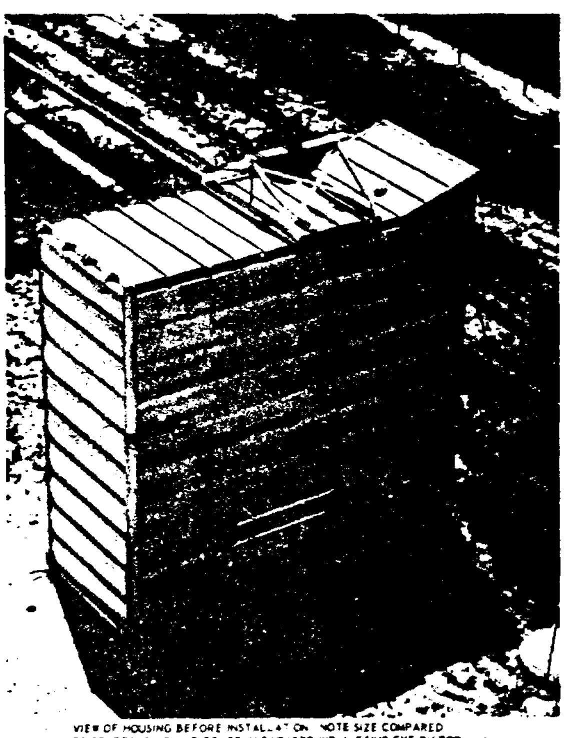


Fig. 9.18. Photo of Savannah River Reactor confinement system filter compartment. Note size relative to fence and scaffolding.

during the next three months while the reactor bay was held for fission-product decay and decontamination. The units were then removed from the building by means of remote handling procedures, lowered to a modified railroad car, and moved to an aboveground storage area where they remain. Before removal from the building, the compartments were filled with expanding urethane foam to fix any loose contamination and to provide a seal if the compartment flapper doors failed to seal. The compartments were removed from the roof by a 7-ton motor crane equipped with a shielded cab, a 120-ft boom, and a special remote-handling hook with long tag lines. The most critical crane operation was lifting the compartment straight up off the roof; the crane operator, located at the base of the building, could not see the load and had to depend on two spotters with binoculars and short-wave radios for directions. One spotter was located on an adjacent roof and the other in a cherry picker attached to the crane. The maximum exposure of the crane operator was 200 mR/hr. The train that moved the compartments to the storage area was made up of the loaded car, three spacer cars, and a locomotive. The train was preceded by a track motorcar occupied by personnel who visually inspected the track, positioned the switches, and opened security-fence gates. A second track motorcar followed the train to restore switches to the normal position and to carry a health physicist who surveyed the track to verify that no contamination was released. The maximum exposure to the train crew was 30 mR/hr. The contaminated compartments were removed from the train by a 100-ton crawler crane with a 65-ft boom and a special remote-handling hook. Exposure to the crane operator was less than 400 mR/hr. The movement of each load to the storage area took 1 hr, and removal and replacement of the contaminated compartments took four days. "In the design of containment systems, much thought is given to the cleanup if gross radioactive contamination occurs. Viewed from this aspect, the aftermath of the accident is a success story for a good containment system that was severely tested."[7]

9.2.6 Remotely Maintainable Fish Filter System[8]

Figure 9.19 shows a series-segmented, remotely maintainable air cleaning facility intended for installation in a shielded vault or underground pit. The interconnecting ducts have tapered-back flanges and are sealed with V-band or ring-clamp couplings that

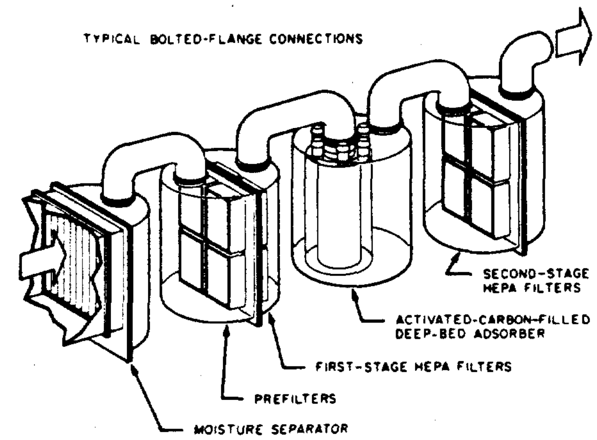


Fig. 9.19. Fish remotely maintainable tub system. Courtesy J. F. Fish, American Air Filter Co.

can be operated by a reach rod or extended-reach tool from outside of the vault or pit. After disconnection, the tubs can be lifted out and replaced by crane, similar to the Savannah River procedure but on a smaller scale. If necessary, contaminated tubs could be withdrawn into a handling cask in the manner described in the next section. Although not shown in Fig. 9.19, the addition of isolation dampers or flapper valves to seal the individual tubs after disconnection would be a simple matter. Fire protection of the carbon-filled deep-bed adsorber is also a simple matter in this design, since it would require no more than filling the tub with water. Being modular, the design offers substantial flexibility and can be adapted to a wide range of application requirements. Individual tubs would be installed in separate concrete shielding vaults and would be easily handled by an overhead crane. The simplicity of the design makes it readily adaptable to remote handling procedures.

9.2.7 Remotely Maintainable TURF Filter System

This system is installed in a radiochemical plant, the Thorium-Uranium Recycle Facility (TURF) at Oak Ridge National Laboratory, Oak Ridge, Tennessee.[9] The filters are installed in a steel enclosure sealed to the building exhaust system ducts by means of the spring-loaded bellows assemblies shown in Fig. 9.20. The bellows are contracted by the hydraulic cylinders to release the enclosure and then returned to the seal position by the springs. The springs also impose a continuous pressure on the gasket of the enclosure while it is in position. An overall view of a similar installation is shown in Fig. 8.9. Each housing contains a bank of three prefilters in series with a bank of three HEPA filters. To replace filters, the isolation valves located in the ductwork are closed, the shielding block is removed, the portable shielded carrier (Fig. 9.21) is moved into position, and the

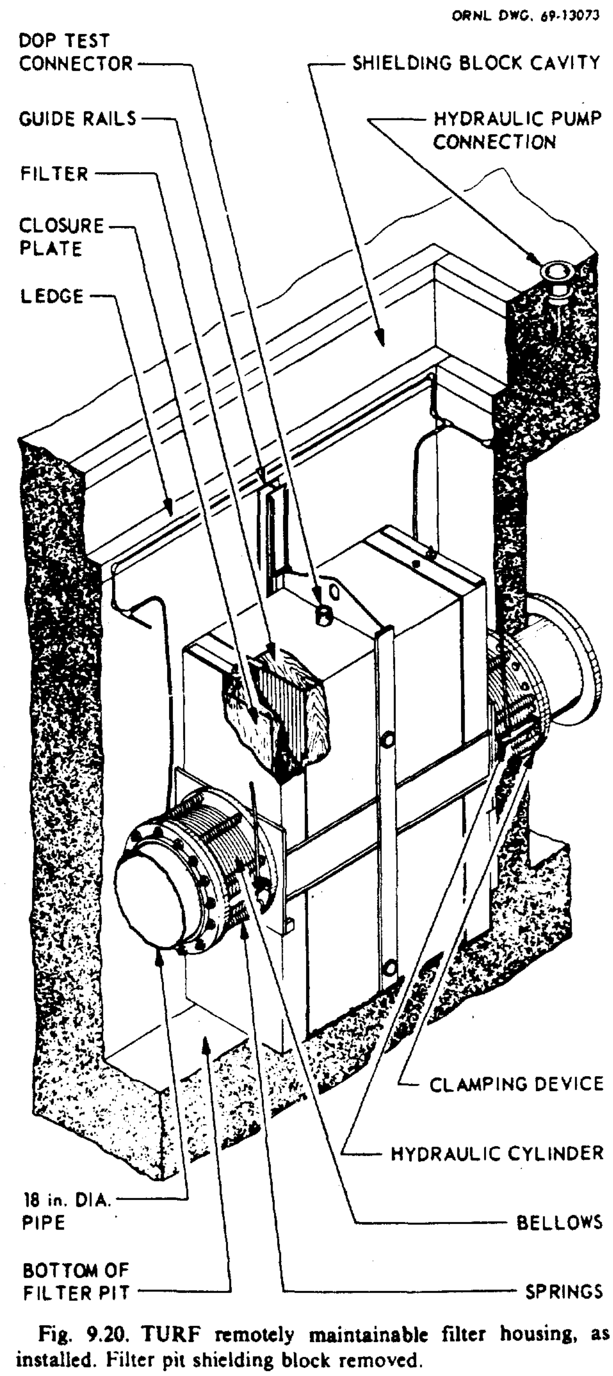


Fig. 9.20. TURF remotely maintainable filter housing, as installed. Filter pit shielding block removed.

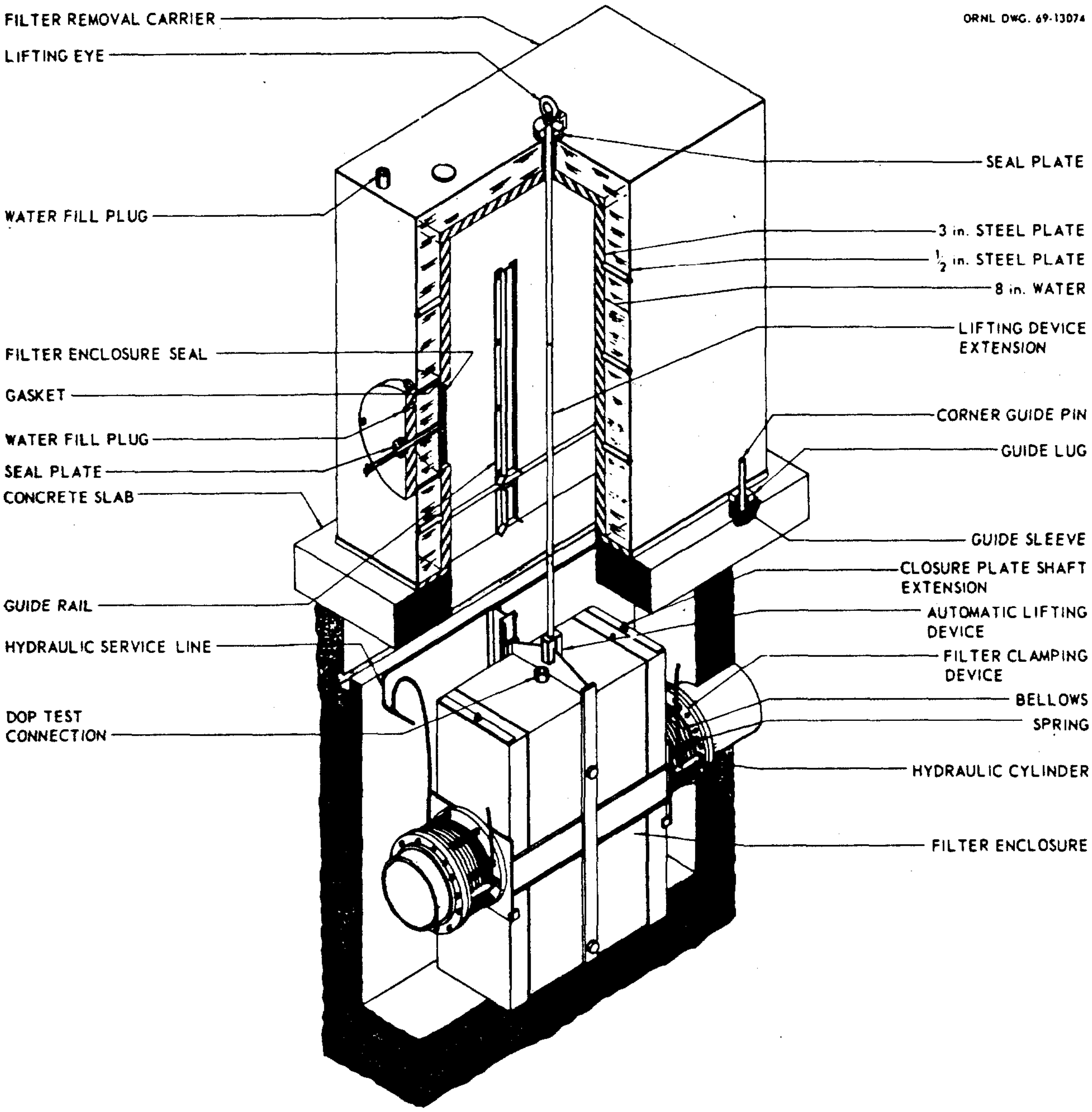


Fig. 9.21. TURF remotely maintainable filter installation with carrier-cask positioned in preparation for removal.

closure plates (Fig. 9.20) are dropped by means of an extended-reach tool. The bellows seals are compressed hydraulically to release the housing, a lifting rod (Fig. 9.21) is hooked into the eye of the housing, and a mobile crane hoists the enclosure into the carrier. After the bottom plate is installed on the carrier, the assembly is lifted to a truck-trailer for removal to the burial ground. The housing is not salvaged.

9.2.8 Remotely Maintainable HWESF Filter Assembly[10]

Figure 9.22 shows one of the remotely replaceable filter housings for the Hanford Waste Encapsulation and Storage Facility (HWESF) at Richland, Washington. This is one of a pair of redundant type 304-L stainless steel housings, each of which contains a bank of six prefilters and two series banks of six (each) HEPA filters. The housings are approximately 5 × 7 × 16 ft long and seal to the ductwork by means of the saddle-and-wedge arrangement shown in Fig. 9.23. Saddle assemblies are seal-welded to each duct opening, and wedge assemblies are bolted to flanges

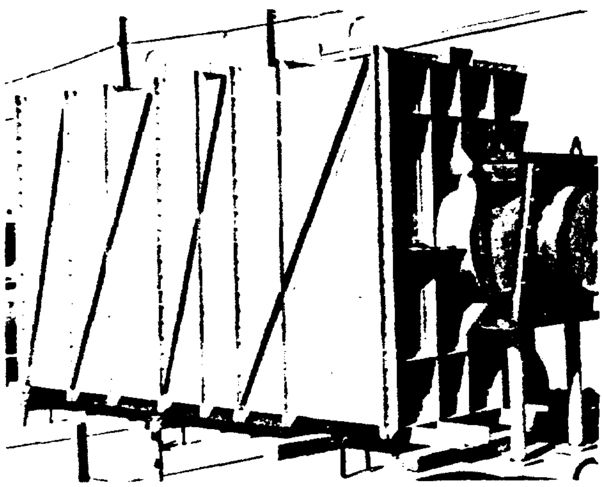


Fig. 9.22. Housing of HWESF remotely maintainable filter installation, Richland, Washington. Note wedge-and-saddle duct connector at right.

at each end of the housing. To install a housing, a gasket is dropped into each saddle and the housing is lowered so that the wedges engage the saddles. Captive nuts on the wedges engage bolts on the top surfaces of the saddles and are tightened to force the wedges down and compress the gaskets. A breakaway bolt, engaging a fixed nut on the upper surface of the wedge (Fig. 9.23*b*), is provided to release the wedge when the housing is to be removed. If heavily contaminated (loadings up to 30 MCi Sr-90 and 30 MCi Cs-137 may be expected on the first-stage HEPA filters), the entire housing can be discarded. The system is designed to seismic category I.

9.2.9 Hot-Cell Filter Systems

First-stage exhaust filters that are installed from inside a hot cell require no special shielding; however, careful planning of filter-change procedures is required to avoid disruption of operations and interference with equipment installed in the cell. Figure 9.24 shows a typical prefilter–HEPA filter installation. The filters are clamped in place with special wing nuts to facilitate handling by the electromechanical manipulators. To remove contaminated filters, the wing nuts are removed and the filters are picked up by the manipulator, placed in a plastic bag or shielded container, and positioned beneath the cell access port preparatory to removal

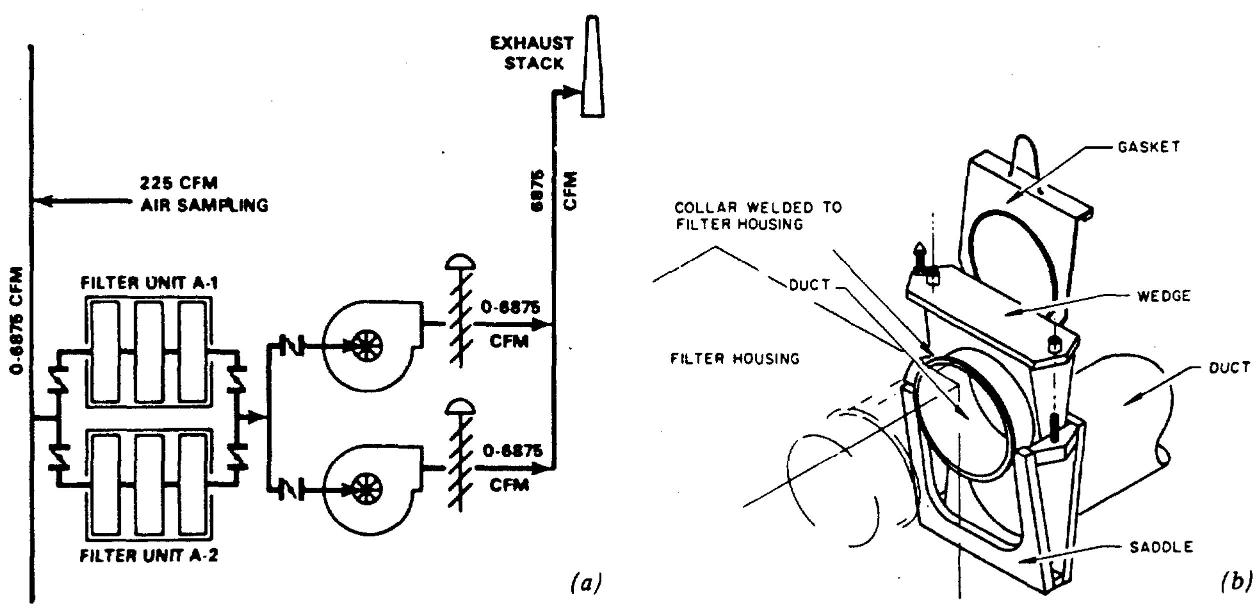


Fig. 9.23. General arrangement and duct-connector details, HWESF remotely maintainable filter system. (*a*) Schematic of HWESF remotely maintainable filter system. (*b*) Wedge-and-saddle duct connector. Wedge assembly bolted to flange of housing, saddle assembly seal-welded into duct. This detail is reversed from the view shown in Fig. 9.22. From E. D. Rice and C. G. Caldwell, "Waste Encapsulation and Storage Facility Ventilation Facility," *Proc. 12th AEC Air Clean. Conf.*, USAEC Report CONF-720823, January 1973.

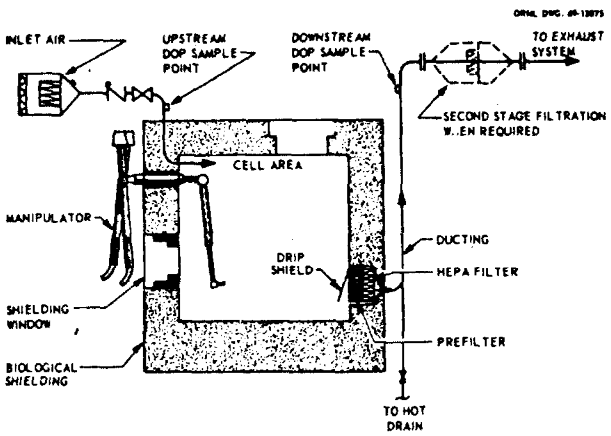


Fig. 9.24. Hot-cell filter installation. First-stage filters replaced remotely from inside of cell, using manipulators. Second-stage filters replaced by contact service techniques.

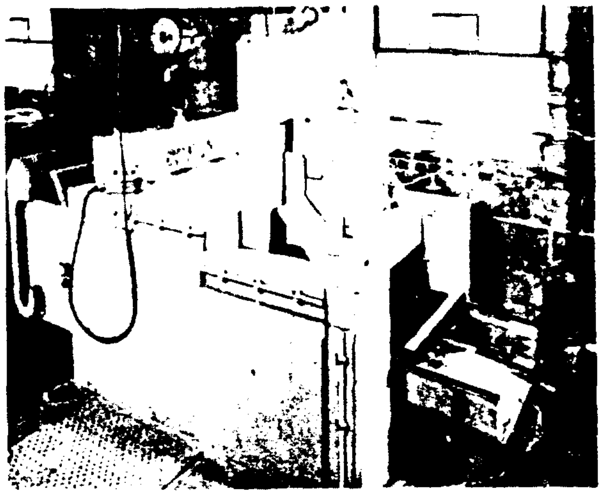


Fig. 9.25. Hot-cell first-stage filter housing designed for semiremote maintenance.

by means of a hoist or extended-reach tool. Filter installation design requirements for this type of installation are discussed in Chap. 6. Second-stage filters are installed outside of the cell, often in a caisson-type enclosure for bag in, bag out maintenance.

Figure 9.25 shows a hot-cell first-stage HEPA filter that is changed from outside the cell. This is an "incessant" filter installation in which the old filter is pushed out of position by the new filter as it is slid into place, thereby keeping the duct opening essentially closed at all times during a filter change. Contamination levels in this installation are high, and the assembly is heavily shielded with lead. A filter is replaced by positioning the lead-shielded carrier (Fig. 9.26) at the discharge end of the housing, removing the shielding doors, and pushing in a new filter. When the contaminated filter is completely inside the disposal can (Fig. 9.26), the door of the carrier is closed and the doors of the housing are replaced. The filters have gaskets on both faces and seal in place by the interference fit between the gaskets and the mating sealing surfaces inside the housing. This is not a highly reliable method of sealing HEPA filters. The installation is costly and requires considerable manpower (three to five man-days) to effect the change of a single 1000-cfm filter. The mechanical features of filter changers of this general type have presented considerable problems at some sites, with the result that the changers are often operated by opening both ends of the housing, removing the old filter by hand, and pushing the new filter in by hand. Incessant filter installations are much overrated.

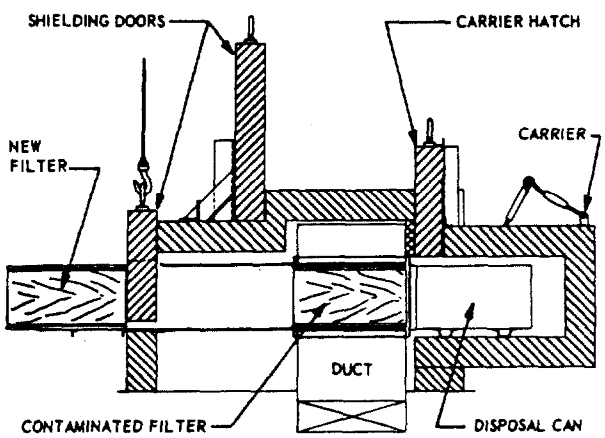


Fig. 9.26. Section through Argonne "incessant" filter changer showing method of operation. When new filter is pushed into position, the old filter is pushed into disposal can in carrier.

9.3 SHIELDING

Ducts and housings may have to be shielded when gamma radiation "shine" exceeds exposure limits specified by federal regulations.[1] Levels as high as 1000 rems/hr may be expected at first-stage filters serving fuel reprocessing or radiochemical operations. Radiation must be reduced to tolerable levels if personnel are to occupy, even occasionally, adjacent areas of the building. Exhaust ducts and housings may have essentially the same hazard classification (Sect. 2.2.1) as the contained space (i.e., glove box, hot cell, building space, containment) they evacuate, and should, therefore, be installed inside building spaces that provide some degree of secondary containment. When such building spaces are occupied, even infrequently, shielding must be provided if gamma radiation is, or could be, a problem. Requirements for and the design of shielding are described in several references, including:

Reactor Shielding for Nuclear Engineers, USAEC Report TID-25951, 1973 (available from National Technical Information Service, Springfield, Va.).

Engineering Compendium of Radiation Shielding, International Atomic Energy Agency, Springer-Verlag, New York, Berlin, vol. 1, *Shielding Fundamentals and Methods*, 1968; vol. 2, *Materials*, 1975; vol. 3, *Shield Design and Engineering*, 1970.

Current information on shielding, including computer codes, can be obtained from the Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Recommendations on the construction of concrete radiation shields can be found in ANSI N101.6.[2]

9.4. NATURAL PHENOMENA

The ability of a system to survive and function during and/or following an earthquake or tornado must be taken into consideration in the design of ESF air cleaning systems. Such systems, by definition (Chap. 1), must be capable of withstanding the effects of a design basis earthquake or tornado and still remain operable and capable of performing their design functions.

9.4.1 Earthquake

The problem of earthquake arises from the possibility of malfunction of fans, dampers, filters, or other functional components of the system, or rupture or structural damage of pressure-boundary components (ducts, housings, fan or damper casings) when the system is subjected to rapid, violent, repetitive shaking or dislocations, either as a lumped mass or as parts of the assembly are dislocated independently relative to one another. Fortunately, the physical masses of air cleaning system components are generally small relative to the massive concrete building elements to which they are anchored; if natural frequencies are greater than about 30 Hz and the parts of any single air cleaning unit (as defined in Appendix D) are anchored to the same building element, a satisfactory earthquake-resistant air cleaning system can be achieved fairly easily. Problems arise when portions of the same air cleaning unit (e.g., different segments of the ductwork) are anchored to different building elements that can vibrate independently. An approach to the design and to design qualification of earthquake-resistant air cleaning systems is suggested in Appendix D.

9.4.2 Tornado

The effects of a tornado manifested in structural damage may arise from missiles, wind, or atmospheric pressure changes that occur when the funnel cloud passes over the building. Assuming that the building is of tornado-resistant construction, damage to the air cleaning system will result mainly from pressure changes that occur in the stack, ducts, and building spaces surrounding the ducts. The current design basis tornado (DBT) hypothesizes that pressure on the building will decrease by as much as 3 psi over a 2-sec period, remain at the depressed level for 3 sec, then return to normal.[11] Because operation of a ventilation system is highly dependent on stable atmospheric conditions to maintain pressure differentials between containment zones of a building and to prevent the release of contaminants, it is likely that system upset, overrunning or reversal of fans, or even reverse flow could occur due to the atmospheric depressurization; failure of dampers could accentuate the condition.[12] On the other hand, stack, ducts, and fans would attenuate the depressurization, and it is unlikely that filters in the exhaust system would experience pressure differentials hypothesized by the Regulatory Guide.[11] The studies of Anderson and Anderson[13] and W. S. Gregory[14] indicate that HEPA filters that meet requirements for nuclear service, unless they have seriously deteriorated, are capable of withstanding any pressure differential they are likely to experience under tornado conditions. The effects of high airflow rates, large pressure differentials, and sustained pressurization or depressurization on air cleaning systems and components are relatively unknown. A study is under way to mathematically model the dynamic effects of tornados and pressure transients on air cleaning and ventilation systems, and to develop methods for describing, analyzing, and calculating the forces to which these systems would be subjected, along with their response to these forces.[12]

Still lacking, however, are solid data on the characteristics of tornados. Investigations indicate that the design basis characteristics presently specified[11] may be too severe. Studies indicate that the maximum wind speed of a tornado probably does not exceed 225 mph, and that the maximum depressurization may be not more than 10% of an atmosphere (~1.5 psi).[15,16] These pressure deficiency values are consistent with preliminary results of a study being conducted for ERDA's Oak Ridge, Tennessee, facilities.[17] There is an indication that the most destructive tornados are the more rapidly moving ones, which implies that the 5-mph translational speed (which controls the period over which the maximum pressure deficiency is applied) of Regulatory Guide 1.76[11] is probably too conservative.[18] Preliminary results of the Oak Ridge study confirm this and indicate a maximum depressurization rate of only 0.5 psi/sec as compared with 2.0 psi/sec in Regulatory Guide 1.76.[17] The Regulatory Guide recognizes that the statistical frequency and severity of tornados vary from one part of the country to another and provides guidance for the application of wind speed and pressure values in particular locations.[11]

Table 9.1. Quantity of combustible material burned to produce a pressure drop of 4 in.wg in HEPA filters[a]

Material burned	Quantity burned to produce plugging in— 50-cfm filter (g)	1000-cfm filter (kg)	Quantity index
Cotton gauze wipes	650	15	13
Cellulose paper wipes[b]	600	13.75	12
Polyethylene film[c]	230	5.3	4.6
Polyurethane-rubber film[c]	110	2.53	2.5
Polyvinyl chloride film[c]	60	1.37	1.2
Amsco solvent[c]	50	1.15	1
D2EHPA solvent[c]	50	1.15	1

[a]Filters operated at nominal airflow capacity; 100% of burning residue reached filters.

[b]Smoke from cellulosic material consisted of large hair-like particles that collected as a coarse, matted, porous layer on the surface, sometimes bridging the space between pleats.

[c]Smoke from plastics and solvents consisted of very small, sticky particles that coated the surface fibers and clogged the interstices between fibers with an impermeable layer.

Note: Flanders Separatorless filter will accommodate approximately 37 to 47% more smoke before plugging than conventional construction.

9.5 FIRE AND SMOKE PROTECTION

9.5.1. Operating Procedures

Operating procedures are the first line of defense against filter failure due to fire. The possibility of fire is sometimes overlooked by the designer because it is assumed that, with fire-resistant filters and steel ducts, there is nothing to burn. This is a misconception. The dust accumulated in ducts and collected in the filters is often highly flammable, and even a fire-resistant filter can be destroyed by sparks, by flaming trash carried into the housing, or by burning dust. Heavy smoke accumulations can cause plugging and subsequent rupture of both prefilters and final HEPA filters when, as is often the case, fans must be kept running to maintain a safe environment. All of these conditions can result from a fire in the contained space. Duct and filter fires may also be caused by transmission from fires in surrounding areas or adjacent equipment, from welding and burning operations conducted within the duct or housing or in adjacent building spaces, or from static discharges within the duct or housing.

Solvent fires present one of the most serious hazards. Not only is a heavy viscous smoke often generated (Table 9.1), but duct temperatures can rapidly build to 1000°C or higher, particularly when the fire occurs right at the duct entrance as in the case of a chemical fume hood, hot cell, or glove box. It is imperative that the quantities of solvents and other flammable fluids permitted in a filtered enclosure or room be severely limited, and that those that are allowed be stored in Underwriters' Laboratories- or Factory Mutual-approved safety containers. Adequate ventilation rates must be maintained under normal operating conditions to keep combustible vapor concentrations within safe limits. When fire results from the ignition of flammable gases that are already at high temperature, such as the off-gas from an incinerator or furnace, duct temperatures may reach 2000°C or higher.[19]

Pyrophoric metal dusts create special hazards. Pyrophoric dust fires in glove boxes, fume hoods, machine-tool hoods, and other small enclosures occur close to the duct entrance and may give rise to duct temperatures on the order of 1800°C or higher. Burning metal fragments may be given off, then captured by the ventilation system and conveyed to the ducts and filters. Since the presence of combustible material cannot be eliminated in this instance, and fire extinguishment by water spray may intensify the fire, recourse often is taken to inert or exclude oxygen from the work environment under normal operating conditions. Argon, helium, nitrogen, and carbon dioxide have all been used as cover gases for this purpose (carbon dioxide freezes moisture in the air and could cause filter plugging by ice crystals). Because pyrophoric metal operations may require oxygen concentrations to be reduced to 1% or less, severe limitations are placed on duct and housing design to avoid air infiltration.

Regular and thorough housekeeping will prevent the accumulation of trash and potentially flammable dust in operating areas. Not so obvious, and therefore generally overlooked, is the use of low-lint clothing by operating and maintenance personnel and the provision of at least moderately efficient filters in the building supply air system and in intakes to contained operating spaces of the building (at least 30% ASHRAE dust-spot efficiency). The major source of lint, one of the most flammable constituents of common dust, is the fretting of clothing as personnel move about in the building. Another major source of dust in exhaust filters is the atmospheric dust brought in with building supply air. The control of such dusts at the source reduces dust loading on exhaust filters and thereby reduces the potential fire hazard in those components. Dust control can also reduce system operating costs; it is much less expensive to change filters in the uncontaminated supply system than in the contaminated exhaust system.

Heat, the third element of fire generation, can be controlled by maintaining adequate ventilation rates for cooling and by excluding, isolating, or shielding items of equipment that produce heat, sparks, or flame. The use of explosion-proof motors and switches in contained spaces should be mandatory, and low-total-heat-output devices such as induction coils and furnaces should be employed instead of Bunsen burners and gas furnaces. One source of heat that may be overlooked is welding and burning within or adjacent to a duct or filter housing. Welding in an adjacent building space has been the cause of at least one serious filter fire.

Maintenance operations often introduce a particular hazard from the standpoint of fire. Operating personnel are generally well indoctrinated in fire prevention and control in their particular areas. Maintenance personnel, however, are not only less familiar with requirements for the particular area, but oftentimes bring into it solvents, paints, lubricants, and other flammable materials in quantities considerably greater than normal operating procedures might permit. Preplanning maintenance procedures may be just as important as preplanning normal operational procedures. Maintenance should be performed in accordance with work-permit procedures that have been reviewed and approved by the plant fire-protection department whenever solvents and other flammable materials are involved.

9.5.2 System Design

The second line of defense against filter and duct fires is the design of the ventilation and air cleaning system. Because the loss of filters may be the most serious consequence of a fire, the first decision must be to use fire-resistant filters, that is, HEPA filters that meet the requirements of UL-586 and prefilters that meet the requirements of UL-900.[20,21] The fire-resistant HEPA filter, in both steel- and wood-cased construction, is designed to withstand air temperatures of 700 to 750° F for at least 10 to 15 min without serious degradation of function, so long as airflow is continued and they do not become plugged. There is, however, a rapid decrease in the tensile strength of the medium at about 450° F; at temperatures above 800° F the fibers begin to break, curl up, and "pill," leaving pinholes in the medium.[22] Extended exposure to temperatures above 800° F will cause destruction of the case of wood-cased filters and warping of the case of steel-cased filters, resulting in bypassing of unfiltered air. Rapid deterioration of all but ceramic-sealed filters can be expected at temperatures above 1200° F. The medium of HEPA filters is thin (0.015 in.) and can be destroyed by incandescent sparks, flaming trash, or burning dust on its surface. The filter can also be plugged rapidly by heavy smoke concentrations, particularly those from burning plastics or solvents, and this can lead to rupture of the medium if the fans have sufficient suction and are kept running. It is essential, therefore, to locate the final HEPA filters where they will be least exposed to the hostile environment of a fire and to protect them with prefilters from sparks, fragments of burning material, smoke, and heat generated by a fire.

Duct-Entrance Filters. Duct fires are serious because they occur in the main conduit leading directly to the filters. Primary protection against duct fires can be obtained by installing at least moderately efficient filters (30 to 45% ASHRAE dust-spot efficiency)[23] at duct entrances to prevent the accumulation of flammable dust inside the ducts. These prefilters provide some protection for the HEPA filters downstream from smoke generated in a fire in the contained space served by the exhaust system. They also provide a sacrificial barrier between that space and the HEPA filters to at least delay the spread of a fire to the HEPA filters. The type of filter used is important, as can be seen from a comparison of Figs. 9.27 and 9.28; the panel or furnace-type prefilter in Fig. 9.27 ruptured after a rapid increase in pressure drop caused by the collection of neoprene smoke and offered only minimal protection to the downstream HEPA filter, even at the beginning of the fire. In the second case, the high efficiency (~85% ASHRAE dust-spot) filter protected the HEPA filter throughout the fire.

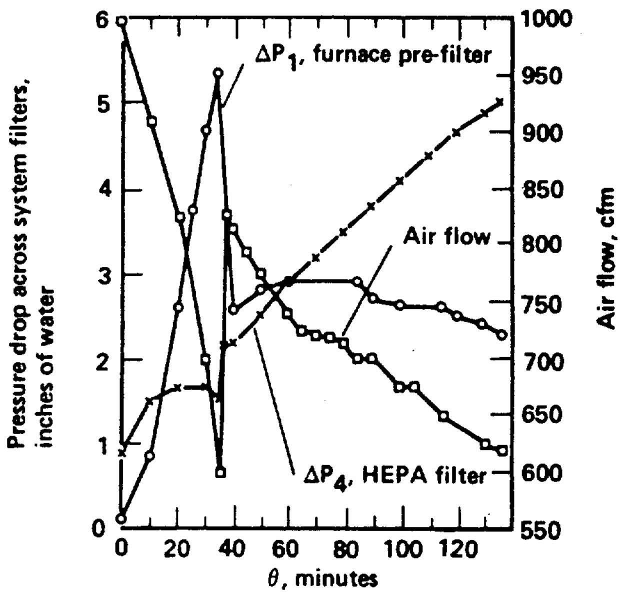


Fig. 9.27. Plot of airflow and resistances of HEPA and furnace-type prefilters against duration of fire in which smoke from burning neoprene is generated. Note rupture of prefilter at about 35 min, the effect of prefilter on prerupture airflow, and poor protection of the HEPA filter, even at early stage of fire. Courtesy Lawrence Livermore Laboratory.

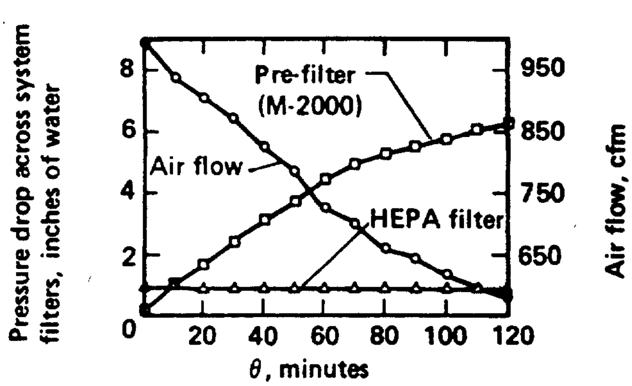


Fig. 9.28. Plot of airflow and resistances of HEPA and 85% efficiency prefilter against duration of fire in which neoprene smoke is generated. Note continued good protection of HEPA filter throughout fire but steady reduction of airflow as prefilter is plugged. Courtesy Lawrence Livermore Laboratory.

Because the duct-entrance filter is the major dust collector, it is also the primary component in which a fire could occur. Protection of the HEPA filter downstream from sparks and burning fragments from the duct-entrance filter may be needed if the distance between them is not great. If it is less than 20 to 30 ft, a fine (20 to 30 mesh) screen may be installed downstream of the duct-entrance filter; such screens must be located where they are convenient for periodic cleaning. Because lint tends to bridge the openings, screens, and coarse filters (e.g., furnace filters), the installation of fine-mesh screens on the face of the duct-entrance filter is not recommended; however, this does not preclude the installation of a 4-mesh screen for physical protection of the filter. For glove-box and hot-cell applications, the duct-entrance filter should be designed for withdrawal into and replacement from the contained space. The filter should also be afforded maximum protection against the effects of or ignition by a fire in the contained space.

Prefilters. Prefilters are usually provided in the central filter house in addition to or in lieu of duct-entrance filters. Again, fire is more likely to occur in the prefilter than in the HEPA filter downstream. Prefilters should never be mounted directly on the face of the HEPA filter or on the opposite side of a common mounting frame with the HEPA (i.e., back-to-back). A spacing of at least 36 in. between the downstream face of the prefilter and the upstream face of the HEPA is recommended, not only for maintainability (Fig. 4.26) but to provide space in which burning fragments and sparks can burn out or settle to the floor of the filter house.

Duct Runs. High temperatures in the central exhaust filter house can be minimized by long runs of duct preceding the housing, by intake of dilution air from streams from other contained or occupied spaces of the building, or by cooling the outside of the duct with water sprays. Cooling by water sprays installed inside the duct has also been employed in some applications. The cooling effect of long runs of duct is illustrated in Fig. 9.29. Without the contribution of dilution air from side streams, at least 100 ft of duct is needed to obtain a 50% reduction of air temperature in a fire of short duration; this approach, therefore, is not always viable.

Flame Arresters. Metal-mesh flame arresters and gas coolers are of limited value for protecting HEPA filters unless they are located well upstream of the filter. Tests by the AEC showed that no commercially

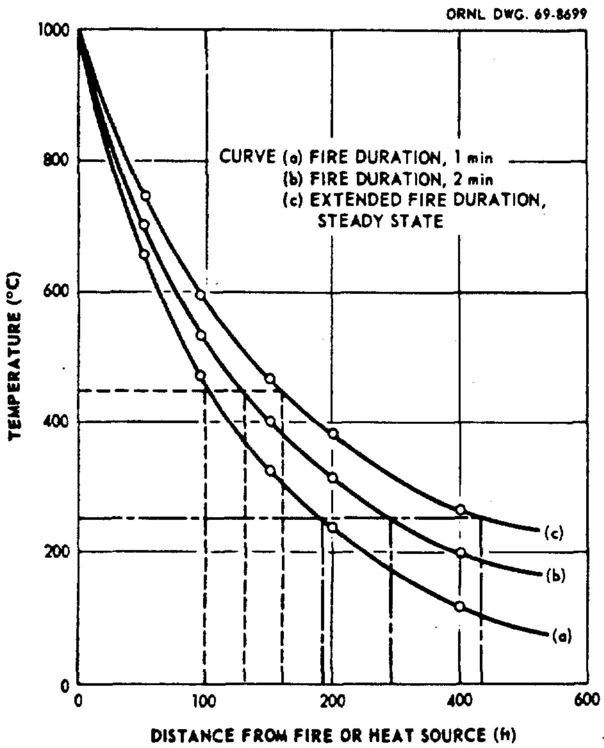


Fig. 9.29. Cooling rate of air in a 12-in.-diam uninsulated duct carrying 1000 cfm of air. Dashed lines show the length required to cool air from initial temperature of 1000°C (1832°F) to 450°C (842°F) and 250°C (482°F) for various fire conditions. From S. E. Smith et al., *Protection Against Fire Hazards in the Design of Filtered Ventilation Systems of Radioactive and Toxic Gas Process Buildings*, UKAEA Report AWRE U-24 65, Atomic Weapons Research Establishment, Great Britain, July 1965.

available flame arrester prevented failure of the HEPA filters when installed close to the filter. To be effective, such devices must have considerable heat capacity and must be located at least 4 to 5 ft ahead of the HEPA filters.

Redundant and Standby Units. Where continued operation of a ventilation system is necessary in the event of fire, system upset, or other emergency, a redundant standby air cleaning unit and fan is essential. The standby unit provides not only the capability of switching to an unimpaired unit in the event of damage to the on-line unit, but also permits isolation of the on-line unit for fire fighting (if the fire is in the filter housing) or repairs, with only minimal interruption of building airflow. A standby unit also permits routine testing and maintenance of the system without interrupting facility operations. This advantage can repay the cost of the extra equipment in only a few years when downtime is a significant expense factor. Manual activation of such standby units is often recommended if there are attendants on duty full-time. Manual changeover gives the time delay needed for personnel to make judgments concerning preplanned emergency procedures, where regard for control of differential pressures between hazard zones of the facility must be considered. A factor sometimes overlooked in such procedures is that switching from a high-resistance bank of used filters to a low-resistance bank of clean filters may also upset the pressure differentials on which proper airflows in the facility depend. Compensation for such pressure differentials is generally provided by control dampers or periodically adjusted balancing dampers in the duct system.

Smoke Venting. A factor sometimes overlooked when supply and exhaust fans can be shut down to fight a fire in a contained or occupied space of the building is that the building intake and exhaust systems, unless properly fire- and smoke-dampered, may serve as flues to vent the building. Venting through the supply air system, unless it is fitted with HEPA filters, will result in the escape of potentially contaminated smoke and gases. On the other hand, venting through the exhaust air cleaning system may plug the duct-entrance filters and/or prefilters and possibly the final HEPA filters, making replacement necessary before post-fire cleanup can begin. Contaminated smoke may also escape through inadvertent building openings such as cracks, thereby bypassing the air cleaning system. This possibility points up the advantage of procedures that assume continued operation of the exhaust system (but shutdown of the supply fans). As for any building construction, adequately designed fire dampers are essential in at least the nonradioactive systems of the building (supply-air and Zone I ventilation systems) and should be considered in the radioactive systems (exhaust, recirculating-cleanup). Some years ago, a study by SMACNA and Underwriters' Laboratories demonstrated that many commercially available fire dampers will warp or fail structurally under fire conditions. It is necessary, therefore, to carefully evaluate such items before installation in supply or exhaust ducts of a nuclear containment system.

Soldered Joints and Connections. Another factor sometimes overlooked is the construction of pneumatic lines for damper and fan control and instrument sensing lines. The use of soft-soldered or plastic tubing in a system where the hazard of fire exists is obviously inappropriate. The failure of such lines under fire conditions could render the entire air cleaning and ventilation system inoperative at the time is most needed.

9.5.3 Fire Detection

The first requisite for effective fire control in a ventilation or air cleaning system, or in a building space that can affect the air handling system, is a sensitive fire detection system. If protective action can be started soon enough, fire in operating areas, ducts, and filter housings may be controllable with a minimum of filter damage and escape of contamination. If a fire gets a good start, however, the filters will probably be lost, and contaminated smoke will be released to the environment or occupied areas of the building. All that can be accomplished in that instance is minimization of casualty losses to the filter housing and mounting frames, or to the building. Assuming proper attention to operational procedures and air handling system design, the likelihood of a fire in the final filters is remote. However, it can never be discounted completely. The same can be said for fires in adsorber systems where continuous airflow must be maintained to remove fission-product-decay heat.

There are three basic types of fire detectors: flame-actuated, smoke-actuated, and heat-actuated. Since airflow carries flame through a filter, preventing its appearance on the upstream face and delaying its appearance on the downstream face until extensive damage has already been done, flame-actuated devices are not suitable. Because the first indication of filter fire is smoke from burning dust or from the volatilized organic binder of the filter paper, smoke-actuated detectors give the most rapid response to a fire. However, the ionization gages used in most smoke detectors may give false indications in radiation fields, and therefore they usually require complex redundant-coincident signaling systems for operational reliability. The products-of-combustion smoke detector can be useful and is discussed below.

Heat-Actuated Detectors. Although slower responding than the smoke detector, certain types of heat-actuated detectors are satisfactory for many duct and filter applications. The rate-compensated detectors and continuous fire detectors (CFD) that have found widespread use in aircraft applications are particularly attractive. The CFD, which consists of a coaxial cable filled with a eutectic salt, is useful in the protection of ducts and large filter banks. The eutectic salt is nonconducting when solid but conducting when melted by the heat given off by a fire in any part of the area "covered" by the cable. When the salt melts, the cable is shorted and signals an alarm or fire-protective device. When the heat is taken away, that is, when the fire is out, the salt freezes and the alarm circuit is opened. However, the detector remains operational and can signal an alarm again should the fire rekindle. To ensure positive personnel response to a fire alarm, true or false, a manual reset is recommended for the audible and visual alarms activated by the detector. Audible and visual alarms should be provided locally and at a central control panel.

The CFD is simple and reliable and requires a minimum of maintenance.[24] Control circuits are simple, and redundancy or coincidency is not required for operational reliability. A wide range of signaling temperatures is available by selection of the appropriate eutectic salt combination, and the system can be tailored to the requirements of the application. CFD systems can be zoned to indicate the general area in which a fire or temperature rise occurs; that is, the system can be segmented, with each segment triggering a separate alarm. When double action such as an alarm on temperature rise to some predetermined level plus activation of fire extinguishing devices at a higher temperature is desired, two cables with different salt combinations can be installed in parallel. Because of its low maintenance requirements, this type of detector is particularly suitable for ducts and other potentially radioactive areas where access is limited.

Products-of-Combustion Detectors. A products-of-combustion detector is probably the most suitable type for carbon-filled adsorbers. Because fires generated by fission-product-decay heat are likely to occur in isolated spots deep within the bed of the adsorber, and because the carbon bed provides excellent heat insulation, flame-actuated (infrared) and heat-actuated detectors are of limited value. However, carbon gives off CO and CO_2 at oxidation temperatures substantially below the flame stage, and the products-of-combustion smoke-actuated detector can, if properly located, sense the incipient fire before it gets a good start. Detectors are needed both upstream and downstream of the adsorbers to eliminate the possibility of falsely indicating fire in the adsorbers when the fire is actually in an operating area of the facility. Whereas HEPA filters can tolerate some modest degree of wetting without significant inpairment,[24] the discharge of deluge sprays to a carbon-filled adsorption system may render the carbon ineffective and also initiate serious corrosion of the stainless steel containers. The downstream detector must be located where excellent mixing of the air coming through all of the beds in the stage has occurred. It must also be very sensitive to offset the effect of dilution of the products of combustion with clean air. Detectors capable of accurately detecting CO and CO_2 at levels of 0.005 ppm above normal background are available. An upstream detector is necessary to discriminate between products of combustion produced in the adsorbers and those produced from fire in an upstream operating area.

9.5.4 Fire Control

Because the possibility of a fire that can affect the final filters cannot be eliminated entirely, some provision for fire fighting is necessary. The minimum protection required in any air cleaning system is the provision for introducing hoses into strategic locations or openings in the duct and filter house. This requires that a water hydrant and hose station be located within a reasonable distance and that provision be made for draining the duct and/or housing during and/or after the application of water. Hoses should be equipped with fog nozzles to provide maximum cooling with minimum application of water. The use of a hose can only be considered a last-ditch solution and cannot be expected to save the filters or prevent the spread of contamination. At best, a hose can serve only to prevent further damage to the filter mounting frames and housing, the duct, or the building; similar observations can be made for the common types of sprinkler systems, both automatic and manually actuated,[25] if installed inside the filter house.

Sprinklers. Common types of sprinklers are useful when installed above ducts to provide cooling or to extinguish fires in adjacent areas. Where the potential of high duct temperatures exists and continued operation of the air cleaning system is essential in the event of fire or explosion in operating areas of the building, the installation of deluge-type sprinklers above the duct is recommended. These sprinklers should be controlled from a CFD installed directly to the underside of the duct and containing a eutectic salt combination commensurate with the desired limiting duct-wall temperature. For large ducts, additional automatic sprinklers, individually equipped with fusible elements, should be installed under the duct for protection against fires in the space below the duct.

The provision of sprinklers within ducts or filter housings is the exception rather than the rule, except for the deluge systems provided on carbon-filled adsorption systems in nuclear power reactors. Fog nozzles, with as fine a droplet-size distribution as possible, are recommended for maximum cooling and smoke-particle capture. To limit the volume of water discharged, consideration should be given to an automatic recycling deluge system. Limiting water discharge is desirable not only from the standpoint of limiting the amount that can potentially get to the filters downstream, but also because the water discharged must be collected and treated as contaminated liquid waste. Individual recycling nozzles (controlled by bimetallic valves on the individual sprinkler heads) are not suitable because the source of heat may be remote from the sprinklers. A deluge system is one in which the sprinklers are normally open with water flow controlled by a quick opening valve in the line leading to the sprinkler heads. When this valve is opened, water is discharged from all the open sprinklers at the same time.

Sprinklers, or more accurately deluge sprays, within the filter house have in practically every case been provided for extinguishing possible fires in the carbon-filled adsorbers of power reactors. These are provided primarily to prevent casualty losses from the fire rather than from any loss of containment. Spraying of water on an adsorber fire is, at best, a last-ditch effort since containment of radioiodine would already have been lost, because both trapped radioiodine and the impregnant added to enhance organic iodide capture desorb at a temperature considerably below the ignition temperature of the carbon. Such desorption would constitute loss of containment for radioiodine.

Protection of Carbon-Filled Adsorption Systems. To prevent loss of containment for radioactive iodine and iodine compounds, carbon-bed temperatures must be maintained at a level at which impregnants and trapped radioiodine cannot desorb. As discussed in Sect. 3.4, this requires that the bed(s) be large enough so that specific loadings of iodine cannot exceed 2.5 mg/g carbon, and that airflow through the bed be maintained at some level in excess of 6 (preferably 10) lin fpm. If bed temperatures can be maintained below that at which desorption of impregnants and trapped radioiodine takes place, there is little likelihood of carbon ignition. If a fire should start, however, there is serious doubt that present-day deluge systems could extinguish it.[26] Total flooding or dumping the carbon into a container of water appears to be the only effective means of extinguishing a carbon-bed fire at this time. Successful tests of fire extinguishment in a proprietary PSU adsorber design were reported by one equipment manufacturer[27] but apparently required large volumes of water. Carbon dioxide and gaseous nitrogen are ineffective against activated carbon fires because the fire feeds on the oxygen adsorbed in the pores of the carbon, and the quantity of liquid nitrogen that would be required to provide effective cooling would be unavailable in most cases.[26]

Smothering Systems. Inert-gas smothering systems have been used with some success in a number of containment systems, particularly in glove box and hot cell applications. The most common type is CO_2 or gaseous nitrogen, with the discharge located within the contained space (glove box, hot cell) rather than in the duct or filter housing. In most cases, supply fans to the contained space must be shut down and exhaust fans must be kept running (at reduced flow, however) to avoid pressurizing the containment either by the discharge of the smothering agent or by the expansion of air and gases due to the fire. Ducts, filter housings, and housing doors must be capable of withstanding the pressures that could prevail in the system under these conditions without leaking. A 34 to 40% concentration of CO_2 or N_2 must be maintained for effective control. Argon and helium have also been used for this purpose, but both may be too expensive for consideration in anything but a closed system (i.e., one in which the fans are shut down and the fire location is isolated).

Halon Systems. Carbon dioxide, nitrogen, and argon systems depend on smothering the fire and present an asphyxiation hazard when employed in occupied or potentially occupied areas. Carbon dioxide systems freeze moisture in the air, creating a plugging potential to filters (if airflow is continued during the fire) and obscuring the vision of personnel fighting the fire or who might be trapped in the treated space. Halon-1301, a chlorinated fluorocarbon, overcomes both of these problems. This agent functions on the basis of chemically tying up oxygen in the air or by reacting with combustion products produced by the fire (the mechanism is not clearly understood).[28] In the quantities required, Halon-1301 causes no obscuration of the work space and presents a minimal toxic or carcinogenic hazard. As with any inerting agent, Halon-1301 works most effectively in a closed space or in one which has minimum airflow. Halon-1301 has been used for fire protection and explosion suppression in many industrial applications and gives promise of relatively inexpensive protection in glove boxes, hot cells, and other nuclear-containment applications. When released to inert a fire in a contained space (hot cell, glove box), the Halon drawn out through the exhaust duct also serves to prevent the ignition of a fire in the duct or in final filters. A concentration of approximately 6 to 8% Halon-1301 in air is sufficient to inert the atmosphere for most combustibles, and a concentration as low as 3 to 4% is sufficient to prevent reignition. This agent is not suitable for metal fires, activated carbon fires, or deep-seated fires. The fact that the gas is nonsuffocating and nonobscuring (in the concentrations required) is a decided advantage for its use in occupied or potentially occupied areas, making the provision of a time delay to evacuate personnel unnecessary. (A time delay is mandatory for smothering agents such as CO_2 and nitrogen.)

Halon systems are often compared unfavorably with other types of inerting systems (CO_2 and nitrogen) and with sprinkler systems because of cost. However, these comparisons are generally based on the unit price of Halon and do not take into consideration the small quantity of agent needed for effective control. When compared with the complexity of a smothering (e.g., CO_2) system or conventional sprinkler system, the Halon system may offer a decided cost advantage in those applications where it can be used.[29] Minimum requirements for Halon systems are given in NFPA 12A.[28] A system engineered specifically to meet the special needs of a nuclear air cleaning system may incorporate special nozzles, flow rates, methods of application, nozzle placement, pressurization levels, and quantities of agent that may differ from those detailed in NFPA 12A. However, all other requirements of that standard must be observed. Applicability, limitations, and precautions in the use of the agent are also covered by NFPA 12A.

Metal Fires. Metal fires, particularly fires in water-reactive metals such as sodium, present special problems. Water and inerting agents such as the Halons cannot be used, and inert atmospheres such as nitrogen and CO_2 require practically the total exclusion of oxygen to be effective. The fire must be treated in the operating space before it can reach the ducts or final filters, which requires an effective duct-entrance filter, preferably one of the HEPA type if the metal dusts are finely divided. However, most of the fire extinguishing agents that are effective against such fires produce copious clouds of dust that, when released, pose a threat of rapidly plugging the duct-entrance filter, which, in turn, poses the threat of overpressurizing the glove box or hot cell and causing the blowback of contamination to occupied spaces of the building. The most effective method to date for extinguishing metal fires is flooding with carbon microspheres (CMS).[30] The CMS method has been shown to be extremely effective against plutonium, sodium, uranium, sodium–potassium (NaK), magnesium, aluminum, lithium, and other fires producing intense heat. The material can be dispensed automatically or manually and produces essentially no dust when dispensed either way. In addition, it has negligible chloride content (and therefore poses no threat to stainless steel equipment and cells), is very easy to clean up because it does not produce dust or airborne particulates, and is inexpensive (<10¢ per pound) and readily available.[31]

9.6 DEEP-BED SAND FILTERS

Sand filters have been used in the ventilation and process exhaust systems of radiochemical processing facilities since 1948. The major attractions of sand filters include large dust-holding capacity, low maintenance requirements, inertness to chemical attack, high heat capacity, fire resistance, and the ability to withstand shock loadings and large changes in airstream pressure without becoming inoperative. Removal efficiency approaching that of a single HEPA filter is claimed if the proper sands are used and the contact path is long enough.* The disadvantages of DBS filters include high capital cost; large area; high pressure drop and power cost; uncertainties in selection, availability, grading, and handling of suitable sands; and the disposal of the spent unit.

Sand filters are deep (several feet thick) beds of rock, gravel, and sand, constructed in layers graded with about 2 to 1 variation in granule size from layer to layer. Airflow direction is upward, and granules decrease in size in the direction of airflow. A top layer of moderately coarse sand is generally added to prevent fluidization of finer sand. The rock, gravel, and sand layers are positioned and sized for structural strength, cleaning ability, dirt-holding capacity, and long life. A cross section of a typical sand filter is shown in Fig. 9.30. Ideally, the layers of larger granules, through which the gas stream passes first, remove most of the larger particles and particulate mass, and the layers of finer sands provide high-efficiency removal. Below the fixed bed of sand and gravel is a course of hollow tile which forms the air distribution passages. The filter is enclosed in a concrete-lined pit. The superficial velocity is around 5 fpm, and the pressure drop across seven layers, sized from 3½ in. to 50 mesh, is from 7 to 11 in.wg. Collection efficiencies up to 99.98% (by in-place test with polydisperse 0.7-NMD DOP) have been reported.[32] The approximate capital cost of a sand filter is $35 per cfm in 1976 dollars.

Sand filters have received renewed interest in the past few years because of the increased concern for the effects of natural phenomena (earthquake, tornado), fire, and explosion and because procurement and maintenance costs of alternative air cleaning

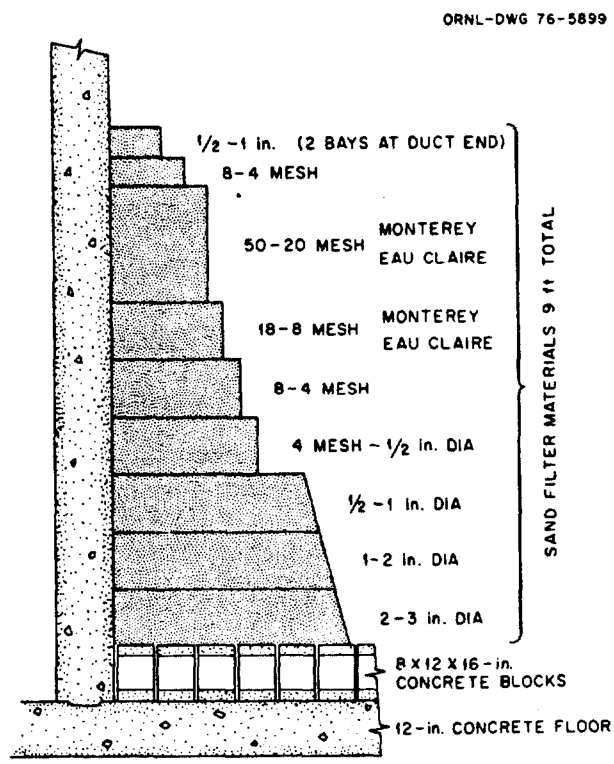


Fig. 9.30. Section through typical sand filter. Table 9.3 lists properties of sand and aggregates used for filtration media. Note course of special hollow concrete block at bottom for distributing inlet air throughout the bed.

*Efficiency tests of sand filters are made with polydispersed DOP aerosol having an NMD of about 0.7 μm, and using the procedures of the in-place test described in Chap. 8. True efficiency tests of HEPA filters, on the other hand, are made with monodispersed DOP aerosol having an NMD of 0.3 μm. In addition, tests of very large units such as sand filters are often made under conditions that sometimes give results that are difficult to interpret. For these reasons, although it can be stated that the efficiency of the sand filter approaches that of the HEPA filter, it cannot be assumed that sand-filter efficiency for submicron particles is actually equivalent to that of the HEPA filter.

methods have increased substantially. Sand filters are characteristically one-of-a-kind designs. They are literally constructed in the field as the gravel is positioned and the sand is poured in place. A view of a sand filter under construction is shown in Fig. 9.31. No standards exist, so most of the information for new designs must come from reports of previous applications. A bibliography and review of sand filters built prior to 1970 was prepared by Argonne National Laboratory.[32]

Following the initial installation of a sand filter at Hanford, nine others were installed at Hanford, Savannah River, and the Midwest Fuel Recovery Plant at Morris, Illinois. All but one[33] of these were designed for cleaning ventilation air from fuel reprocessing facilities, and only four (all at Savannah River) are currently used for this purpose. There is a sand filter in the roof of the Zero Power Research Reactor[34] at Idaho Falls, but it is for emergency exhaust cleanup only and is not operated under normal conditions. Details of existing U.S. sand filters are given in Table 9.2. Properties of sands and aggregates used as the filtration media of these filters are given in Table 9.3.

9.6.1 Design of Deep-Bed Sand Filters

A rough approximation of the collection efficiency of sand, on an activity basis, is given by the following equation:[35]

$$\eta = 1 - \exp(-KL^{1/2}V^{-1/3}D^{-4/3}) , \qquad (9.1)$$

where

η = fractional collection efficiency on a radioactivity or mass basis;
L = depth of fine sand, ft;
V = superficial gas velocity, fpm;
D = average sand grain diameter, in.;
K = proportionality factor.

(Note: values of L, V, and D vary with sands from different sources of the same mesh size and must be determined experimentally for any given sand.)

Values for the proportionality constant, K, for several sands tested at Hanford are

Type of sand	K
Hanford	0.053
AGS flint	0.045
Rounded grain sand (Ottawa, Eau Claire, Monterey)	0.035

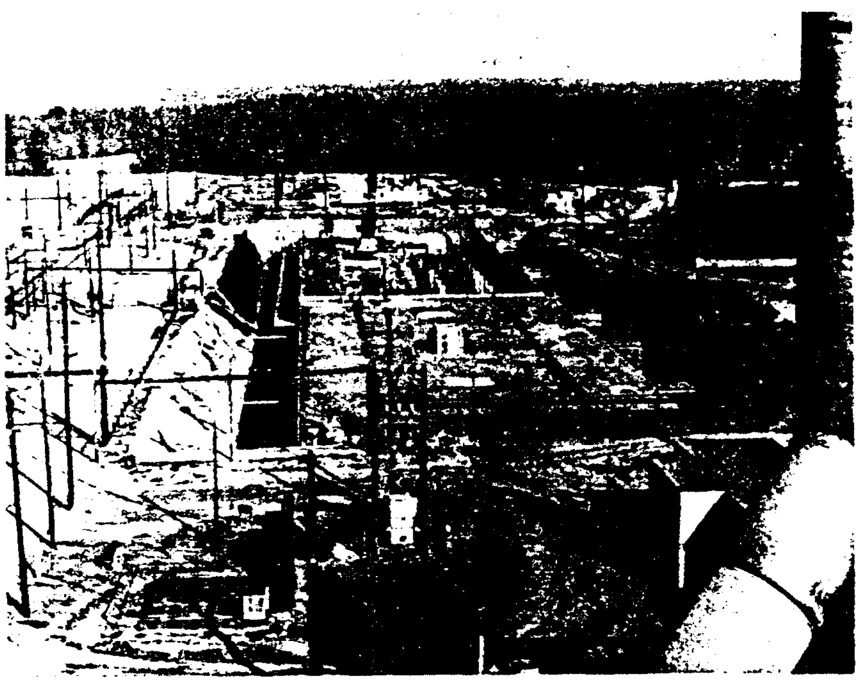


Fig. 9.31. View of sand filters at ERDA Savannah River Laboratory. Existing sand filter in foreground, new filter under construction beyond.

Collection efficiency on a radioactivity basis gives a higher number than the collection efficiency on a count basis, as reflected by the DOP test, since larger, more easily collected particles may carry more radioactivity and bias the analysis to give more worth to larger particles. The relationship between count and activity collection efficiency cannot be determined without accurate information on aerosol size distribution and the relationship of aerosol size to radioactivity.

The approximate void fraction of a sand bed is generally about 0.4. Sand permeability tests showed that intense vibration can cause extreme compaction, resulting in near doubling of the pressure drop.[36–38] Factors that must be considered include the effects of compaction, steam injection, relative humidity, and velocity change on efficiency and pressure drop. Besides permeability and filtration requirements, the sand must be abrasion- and fracture-resistant and must resist corrosion from the fumes likely to be present in the exhaust air stream.

Filter life is determined by the increase in pressure drop and the decrease in gas flow caused by the collection of solids within the sand bed. Filter life can be significantly reduced if solids collection is concentrated in small fractions of the bed or on the finer sand. Uniform concentration of coarse aggregate layers upstream of the fine sand layer tends to maximize filter life.

Clogging of sand filters is aggravated by local decreases in porosity at the interfaces between graded layers. The mixing of aggregates (sand, gravel) at the interfaces usually results in a lower void fraction at the interface than if no mixing is permitted. The extent of reduction in void fraction depends on the characteristics of the aggregates and on the technique used to charge them into the filter bed. The lowest layer may require hand placement for the first few inches so that no rocks fall through the openings in the distribution blocks (Fig. 9.32). Significant improvement in filter life can be obtained by careful attention to loading.

Table 9.2. Dimensions and operating data of existing U.S. sand filters

DBS filter No.[a]	Plan dimensions[b] (ft)	Design flow (cfm)	Design superficial velocity (fpm)	Design pressure drop (in.wg)	Date of initial operation	Present status of DBS
1	108 × *46*	25,000	5.0	5.0	1948	Standby
2	108 × *46*	25,000	5.0	7.0	1948	Standby
3	96 × 96	40,000	4.3	10.0	1950	[c]
4	85 × 85	40,000	5.5	12.0	1951	Active
5	*240* × 100	115,000	4.8	~10.0[c]	1954	Standby
6	*240* × 100	115,000	4.8	9.2[c]	1955	Standby
7	360 × 100	210,000	5.8		1975	Active
8	360 × 100	210,000	5.8		1976	Active
9	140 × *103*	74,000	5.1		1974	Active
10	72 × *78*	32,000	5.7		1974	[d]
11	50 to 62.5(diam)	[e]	[e]		1968	Active[e]

[a]Filter identification
1. T Plant, Building 291-T, Hanford West Area, Richland, Wash.
2. B Plant, Building 291-B, Hanford East Area, Richland, Wash.
3. U Plant, Building 291-U, Hanford, Richland, Wash.
4. Redox Facility, Building 291-S, Hanford, Richland, Wash.
5. F Area, Building 294-F (old), Savannah River Plant, Aiken, S. C.
6. H Area, Building 294-H (old), Savannah River Plant, Aiken, S. C.
7. F Area, Building 294-1F (new), Savannah River Plant, Aiken, S. C.
8. H Area, Building 294-1H (new), Savannah River Plant, Aiken, S. C.
9. SRL, Building 794-A, Savannah River Laboratory, Aiken, S. C.
10. Midwest Fuel Recovery Plant (MFRP), Morris, Ill.
11. Zero Power Plutonium Reactor Facility, Argonne National Laboratory, Idaho Falls, Idaho.

[b]Inlet side shown first, outlet side italicized.
[c]Unit in service, process operation was discontinued in 1975.
[d]MFRP is not engaged in reprocessing, only storage; sand filter is active.
[e]This is an emergency relief system.

Table 9.3. Properties of sands and aggregates used in existing U.S. sand filters

Property		Filter No.[a]									
		1	2	3	4	5	6	7	8	9	10
Depth of bed, ft		9	8.5	8	8	8	8	7.5	7.5	7.5	8
Number of layers		9	8	7	7	7	7	6	6	6	
		Depth of layers (in.)									
Granule size range, mesh (unless in. noted)											
Layer A	3–2 in.	12									
	$2\frac{1}{2}$–$1\frac{1}{4}$ in.		12								
	3–$1\frac{1}{4}$ in.					12	12	12	12	12	
	3–1 in.			12	12						18
Layer B	2–1 in.	12									
	$1\frac{3}{4}$–$\frac{5}{8}$ in.		12	12	12						12
	$1\frac{1}{2}$–$\frac{5}{8}$ in.					12	12	12	12	12	
Layer C	1–$\frac{1}{2}$ in.	12									
	$\frac{3}{4}$ in.–~6		12	12	12						
	$\frac{5}{8}$–$\frac{1}{4}$ in.					12	12	12	12	12	
Layer D	$\frac{1}{2}$ in.–4	12									
	$\frac{3}{8}$ in.–3										12
Layer E	4–8	12	6	6	6	6	6	6	6		6
	$\frac{1}{4}$ in.–8									6	
Layer F	8–20	12	12	12		12	12	12	12	12	6
	8–18				12						
Layer G	20–40										
	30–50					36[c]	36	36	36	36	
	20–50			36	36[c]						36

[a]See Table 9.2 for location corresponding to number.
[b]Cable and wire mesh of footnote *a* catenary cross-section support, deep bed.
[c]Removed 12 in. from G layer, July 1972, to reduce pressure drop.

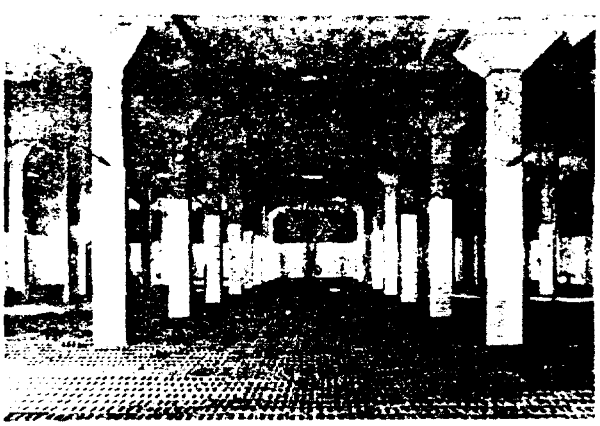
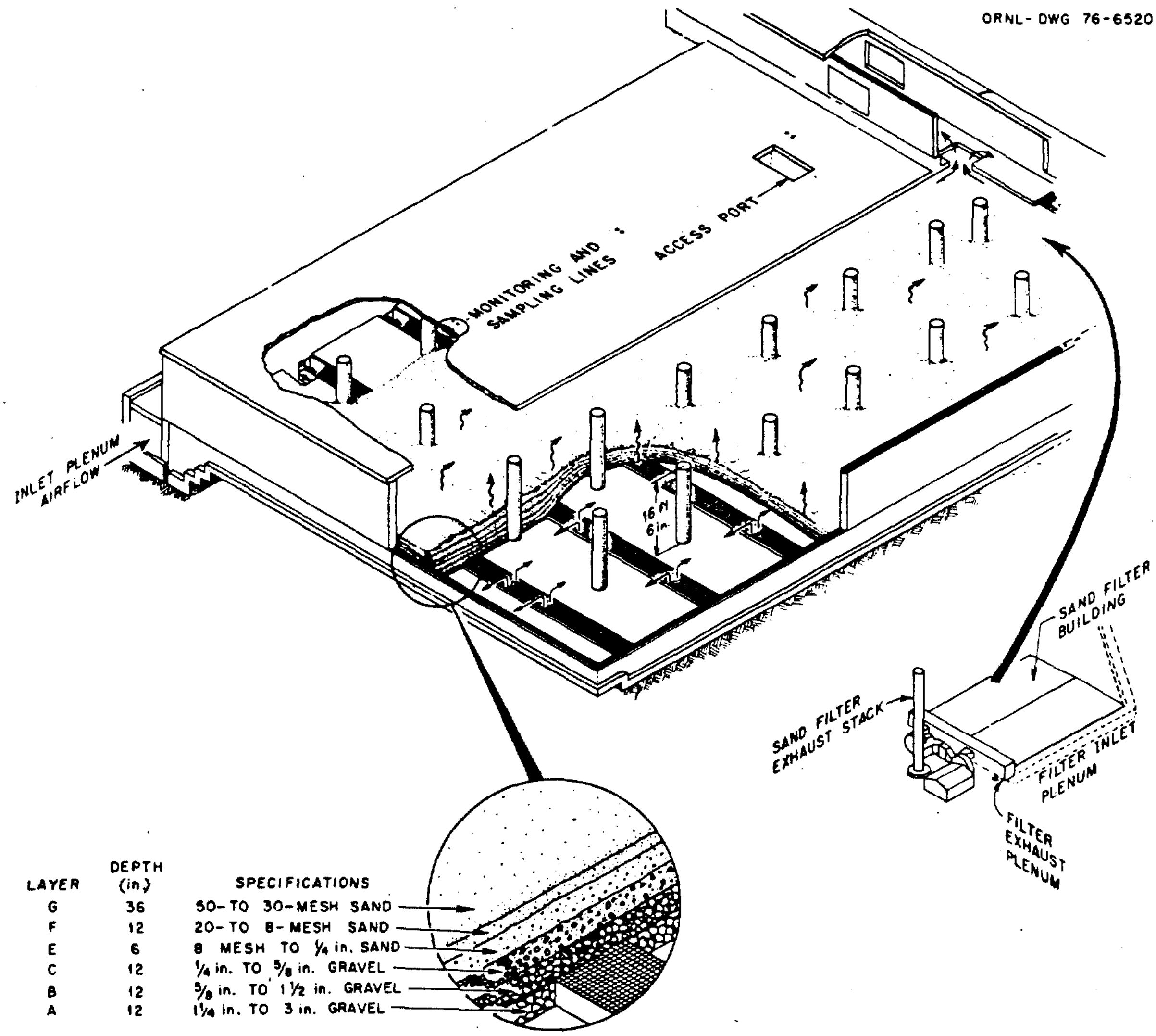


Fig. 9.32. Interior of new sand filter at Savannah River Laboratory before loading of sand and aggregate. Note course of hollow tile for air distribution. When finished, sand will come to the level marked by arrows.

The sand filter housing is a poured concrete structure, partially underground, with walls capable of withstanding the design basis earthquake without cracking and the design basis flood without leaking. The floor has channels for distributing the incoming air and is covered by the special hollow block shown in the view of an empty sand filter (Fig. 9.32). An isometric of this filter is shown in Fig. 9.33. The floor and the distribution system must bear the weight of the sand column above it. With corrosion and aging, withstanding this weight has been a problem in some sand filters. The floor should be sloped to a drain and have a built-in capability for drainage if it becomes necessary. It is often prudent not to connect the drain line, so that a determination of what to do with the drainage can be made after the event if flooding occurs. The filter should be on the suction side of the



LAYER	DEPTH (in.)	SPECIFICATIONS
G	36	50- TO 30-MESH SAND
F	12	20- TO 8-MESH SAND
E	6	8 MESH TO ¼ in. SAND
C	12	¼ in. TO ⅝ in. GRAVEL
B	12	⅝ in. TO 1½ in. GRAVEL
A	12	1¼ in. TO 3 in. GRAVEL

Fig. 9.33. Overall isometric view and details of new sand filter at Savannah River Laboratory.

fan so that it is negative to the atmosphere and all leakage is inward.

When a sand filter is used in series with HEPA filters, it should be upstream of the HEPA filters. In this position, the high dust-holding, fire-resistance, and pressure-surge-attenuating characteristics of the sand filter can protect the HEPA filters that provide the final containment barrier.

9.6.2 Plugging of Deep-Bed Sand Filters

Some filters have experienced plugging at low dust loadings. In one case, the plugging was caused by moisture entering through cracks in the concrete sidewalls of the unit.[39] In another instance, plugging was caused by crystal growth in the filter media fines, probably due to a reaction of nitric acid vapors from the process building with calcite, with dolomite present in the original sand, and with cement dust generated by severe erosion and acid attack on the concrete entry ducts and support structures.

9.6.3 Disposal of Spent Media

Deactivation of existing filters is generally accomplished by sealing and abandoning the filter. Spent media are stored in place within the unit. The total unit is replaced by a new filter located close by. Present government regulations for radioactive solid waste, though unclear, may rule out such in-place disposal in the future. If the material is handled as high-level radioactive waste, each 1000-cfm capacity of filter would require about two hundred 55-gal drums for disposal.

9.7 DEEP-BED GLASS-FIBER FILTERS

9.7.1 Introduction

Another type of large-capacity long-lived filter that has been used successfully for the prefiltration of ventilation and process air in a number of AEC/ERDA radiochemical and fuel reprocessing operations is the deep-bed glass-fiber (DBGF) filter. Developed as an alternative to the more costly sand filter, the DBGF filter employs a medium that has more controllable physical features and more assured availability than filter-grade sands, permits a larger airflow per unit of volume at lower pressure drop, has lower operating costs, and potentially lower spent-unit disposal cost than a sand filter of equivalent airflow capacity. On the negative side, the DBGF filter does not have nearly the particle-collection efficiency of the sand filter; has less corrosion resistance, particularly from hydrogen fluoride, and less fire resistance; and lacks the heat-sink and self-repair properties and capability of the sand filter to snub shocks and high-pressure transients.

DBGF filters are deep (8 to 84 in.) beds of compacted fiberglass insulating wool contained in stainless steel boxes (trays) having opaque sides and perforated screens at the top and bottom. Units as small as 200-cfm airflow capacity, or smaller, have been employed in process off-gas systems, and units as large as 150,000-cfm airflow capacity have been used in building and cell-exhaust installations. Figure 9.34 shows a view of the newly completed DBGF filter at the Idaho National Engineering Laboratory (INEL) and illustrates the typical construction details of a large unit. The first use of a DBGF filter was a 250-cfm unit in a dissolver cell exhaust at Hanford in 1950.[40] By 1953, 11 units with airflow capacities from 200 to 20,000 cfm had been installed.[41,42] A 126,000-cfm unit was installed in the canyon exhaust of the Purex plant at Hanford in 1955,[43] and a 150,000-cfm unit has just been completed for the Idaho Chemical Plant at INEL. DBGF filters have also been used successfully in a number of hot-cell applications for process off-gas cleanup.

9.7.2 Design and Operation

The INEL unit shown in Fig. 9.34 is typical of current large-scale DBGF filter design. The filter is housed in a 40 × 80 × 14-ft-high concrete-lined pit and is divided into four individually isolable bays. Each bay contains four stacks of filter trays arranged in parallel, and each stack contains five trays in series. The trays are supported by and seal to steel embedments in the concrete. Tray (bed) depths and the packing densities of the fiberglass wool in the trays are given in Table 9.4. Airflow is upward and, at the design airflow of 50 fpm, initial (clean filter) pressure drop is about 1.5 in.wg. The final pressure drop, after a total dust loading estimated to be 10,500 lb, is 8 in.wg. In-place tests of the filter, using 0.7-μm-NMD DOP aerosol, indicated an efficiency of about

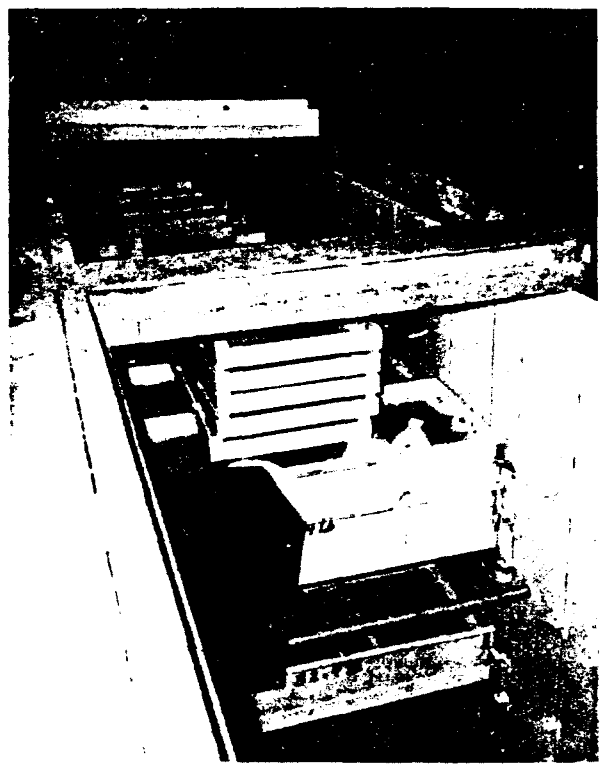


Fig. 9.34. View of the DBGF filter at the Chemical Processing Plant, Idaho National Engineering Laboratory. Courtesy Allied Chemical Co.

Table 9.4. Depth and media-packing densities of an Idaho chemical processing plant DBGF filter[a]

Stage	Bed depth (in.)	Packing density (lb/ft^3)
5	18	3.0
4	18	1.5
3	18	1.5
2	15	0.7
1	15	0.7

[a]Airflow direction is upward.

80%, but there is some question as to the accuracy of this value because of difficulties of introducing the DOP and obtaining a meaningful upstream sample. The calculated mass efficiency or arrestance is 99.95% (i.e., a mass decontamination factor of 2000).

Early predictions of achievable DBGF filter efficiencies were overly optimistic. Although some eight fiber types were tested and gave promise of efficiencies approaching that of a HEPA filter, only one, the Owens Corning Fiberglas type 115K, was found to be satisfactory under field conditions.[43] The key to 115K fiber performance is that it has a permanent curl that, when the fiberglass wool is packed into trays at packing densities of from 0.7 to 9 lb/ft^3, resists matting; the other fibers, being straight, tended to pack down under operating conditions, resulting in extremely high pressure drop at even low airflow velocity.[44] The satisfactory operation of a DBGF filter is a function of collection efficiency, airflow and pressure-drop characteristics, and filter life, and depends on maintainability, testability, and details such as tray, joint, and overall filter design, flow and service connections, instrumentation, and disposability of spent media. Airflow capacity is a function of filter size. The mass collection efficiency and pressure drop at design airflow velocity can be determined from the following equations:[43,45]

$$\log DF_r = CL^a P^b V^c \,, \tag{9.2}$$

$$\eta_r = 1 - \frac{1}{DF} \,, \tag{9.3}$$

$$R = KL^x P^y V^z \,, \tag{9.4}$$

where

DF_r = decontamination factor, based on radioactivity (dimensionless);
C = constant (from Table 9.5);
L = bed depth, in.;
P = fiber packing density, lb/ft^3;
V = airflow velocity, fpm;
η_r = collection efficiency based on radioactivity (decimal);
R = resistance, in.wg;
K = constant, from Table 9.5;
a, b, c, x, y, z = empirical constants, from Table 9.5.

Values of the constants and exponents determined for several of the fibers tested at Hanford,[43] including fiber 115K, are given in Table 9.5. The DF and pressure drop of a multibed (series) filter are the sums of the DFs and pressure drops, respectively, of the individual beds. From these equations, a filter filled with 115K fiber and operated at an airflow velocity of 20 fpm would require 40.62 in. of bed depth to produce a DF_r of 2000. DF_r is more closely related to mass DF, or arrestance, than it is to number DF, the value used for the HEPA filter.

As with the sand filter, the collection efficiency of the DBGF filter increases with increasing velocity through the bed; however, collection efficiency for small (submicron) particles drops off with increasing velocity, because the effectiveness of the diffusion mechanism (on which trapping of submicron-sized particles is dependent) decreases (Figs. 2.8 and 2.17). By careful selection of packing density, bed depth, and airflow velocity, collection efficiency equivalent to that of a group II to group III ventilation air filter (Sect. 3.3) can be achieved. The other fibers tested, although found to be unsatisfactory for the DBGF unit, have been used in the media of replaceable medium filters (Fig. 3.7) installed in series with and downstream of the DBGF filter. Equations (9.2) through (9.4) can also be used for determining the DF_r, efficiency, and pressure drop of these unitized modular filters. Some of the earlier Hanford canyon-exhaust installations employed a DBGF forefilter followed by a bank of afterfilters (Fig. 3.7) filled with AA-fiber medium.

Although there is an economic incentive to increase velocity through the DBGF filter (bed area is inversely proportional to volumetric flow rate, and

Table 9.5. Fiber characteristics, constants, and exponents for calculating decontamination factors and pressure drops of DBGF filters [Eqs. (9.2) and (9.4)]

Type of fiber	Type glass	Fiber diameter (μm)	Constants to be used in Eqs. (9.2) and (9.4)							
			C	a	b	c	K	x	y	z
AA	E	1.3	4.6	0.8	1.0	−0.2	0.082	1.0	1.5	1.0
B	E	2.5				−0.25				1.0
115K	C	30	0.054	0.9	0.9	−0.4	0.00020	1.0	1.5	1.0

capital cost is directly proportional to bed area), experience shows that a maximum velocity of about 50 fpm is desirable. Airflow in units larger than 10,000-cfm airflow capacity is usually upward, with filter beds installed horizontally, as shown in Figs. 9.34 through 9.37. Although there are currently no standards for DBGF filters, it is likely that future regulations will require that they be capable of withstanding natural phenomenon incidents, as discussed in Sect. 9.4. Large units are in most cases installed underground or partially underground, with earth cover, for the attenuation of collected radioactivity. If moisture is likely to be present, stainless steel cladding of the concrete pit is recommended (Sect. 9, ANSI N101.6).[46] To avoid plugging and premature failure or excessive resistance, provision for backflushing is sometimes made. Backflushing sprays are generally necessary only for the first one or

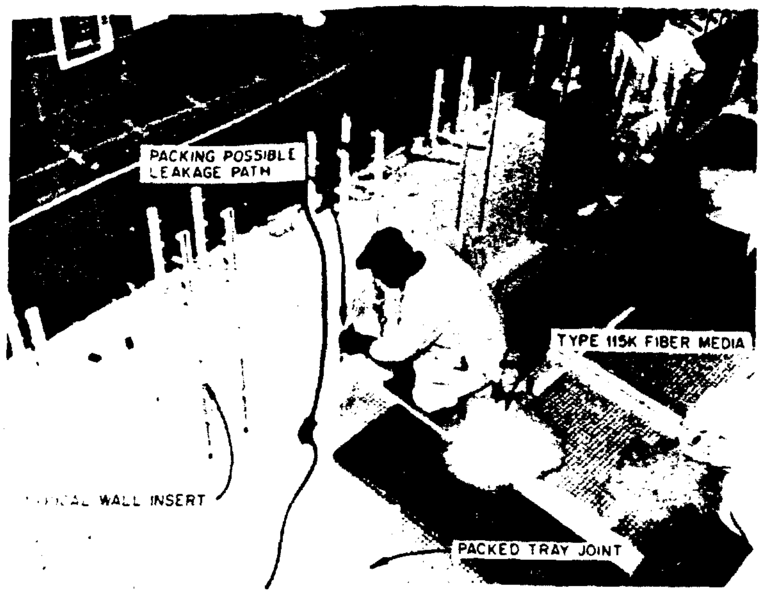


Fig. 9.35. Joints between walls and trays of 291-A-2 DBGF filter, Purex plant, being packed with loose fiber to prevent bypassing. Courtesy Atlantic Richfield Hanford Co.

Fig. 9.36. Packing media into trays of a 291-A-2 DBGF filter under construction at the Purex plant. Note packed wall joints, embedments in walls. Courtesy Atlantic Richfield Hanford Co.

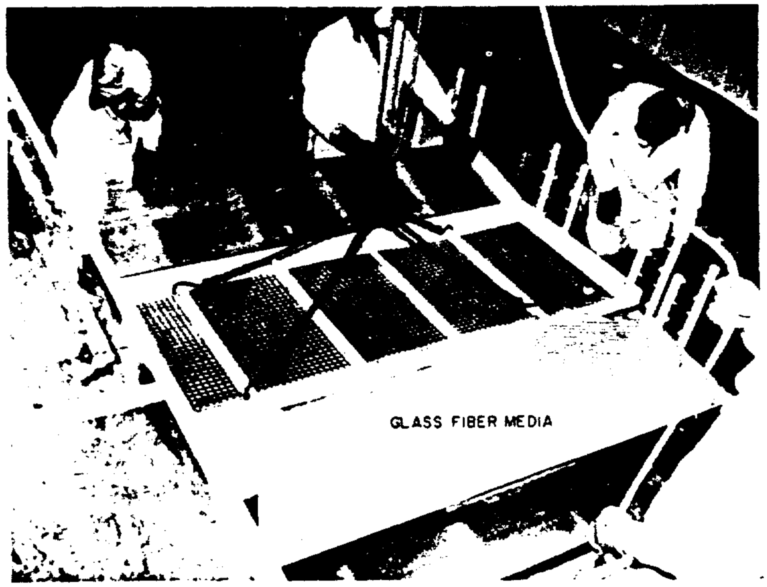


Fig. 9.37. Installing top screen on fiber-backed tray of a 291-A-2 DBGF filter under construction at the Purex plant. Courtesy Atlantic Richfield Hanford Co.

two stages of the filter. Large DBGF filters should be segmented (Sect. 2.4.12), with each section contained in an isolable, individual vault, as in the INEL filter, to provide flexibility for maintenance and testing. Provisions for in-place testing with DOP should be built into the filter, with particular attention given to the ability to achieve a satisfactory air–aerosol mixture entering the filters and the ability to take reliable samples immediately upstream and at a point downstream, where there is good mixing of the filtered air and penetrating contaminants.

Instrumentation to establish the dew point of the inlet air, the flow rate, the pressure drop across individual trays (not stages), and the inlet air temperature is recommended. The capability of monitoring the radiation level in various parts of the filter and the provision for removing strategically located samples of media from time to time are desirable.

In large filters, the medium is contained in modular, interchangeable trays. Figure 9.38 shows the bottom screen assembly of a typical tray. Besides holding the filter medium in place, the trays are also designed, and must be structurally reinforced, to apply the compressive force required to give the desired packing density. The compressive pressure necessary to produce the required packing density of 115K fibers, over the range of from 0.7 to 9 lb/ft^3, can be found from the following equation:

$$P_c = 2.1\,(P - 0.6)^2\,, \qquad (9.5)$$

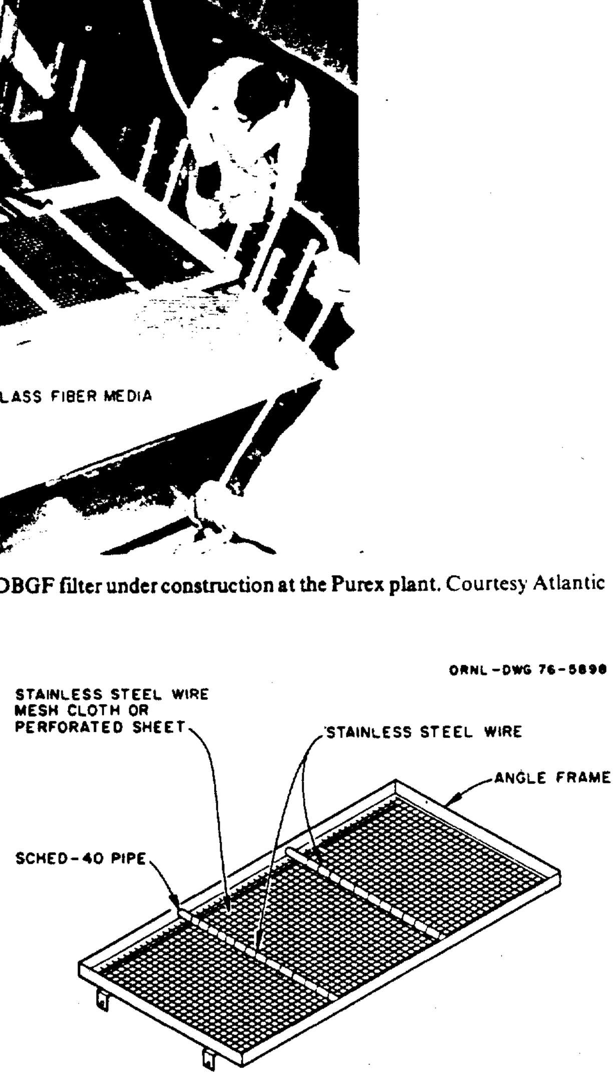


Fig. 9.38. Typical top or bottom screen for DBGF filter trays.

where

P_c = compressive pressure, lb/ft^2;
P = packing density, lb/ft^3.

Compressing type 115K-fiber insulating wool to a density of 9 lb/ft^3 requires a compressive pressure of about 150 lb/ft^2.

9.7.3 Wet Operation

Although reports have indicated that a DBGF filter can provide satisfactory service when operated so that water continuously condenses in the beds,[47] wet operation is not recommended. Downstream filters, whether HEPA or the extended-medium type shown in Fig. 3.7, will not tolerate high moisture loadings and lose performance, or deteriorate, when operated continuously wet.[44,45]

9.7.4 Plugging

The high dust-holding capacity of the DBGF filter should not induce the operator to totally forego the pretreatment of air discharged to it. Some contaminants must be removed from the process exhaust streams, and the operator must be as sensitive to the limitations of the DBGF filter as he is to the limitations of the HEPA filter. The first large DBGF filter at the Hanford Purex plant was originally operated in a downflow condition. The gradual buildup of ammonium nitrate on the upper fiberglass layers finally increased the pressure drop, over a period of nine years, to the point that the system could no longer meet canyon ventilation airflow requirements.[48] The effect of plugging is shown in Fig. 9.39, which illustrates the effect of loading a 2-in.-thick bed of 115K-fiber medium, packed to a density of 6 lb/ft^3 at 25 fpm airflow velocity, with methylene blue. As the load increased from 0 to 200 grains of methylene blue per square foot, the pressure drop across the bed increased by only 0.5 in.wg. With an additional 60 grains/ft^2, however, the pressure drop increased to 5.5 in.wg, or ten times that at the start of this additional loading. This increase suggests possible difficulties in the operation of the filter. If particulate concentrations in the exhaust stream were constant over the life of the unit, the timing of the sharp knee of the load vs pressure-drop curve could

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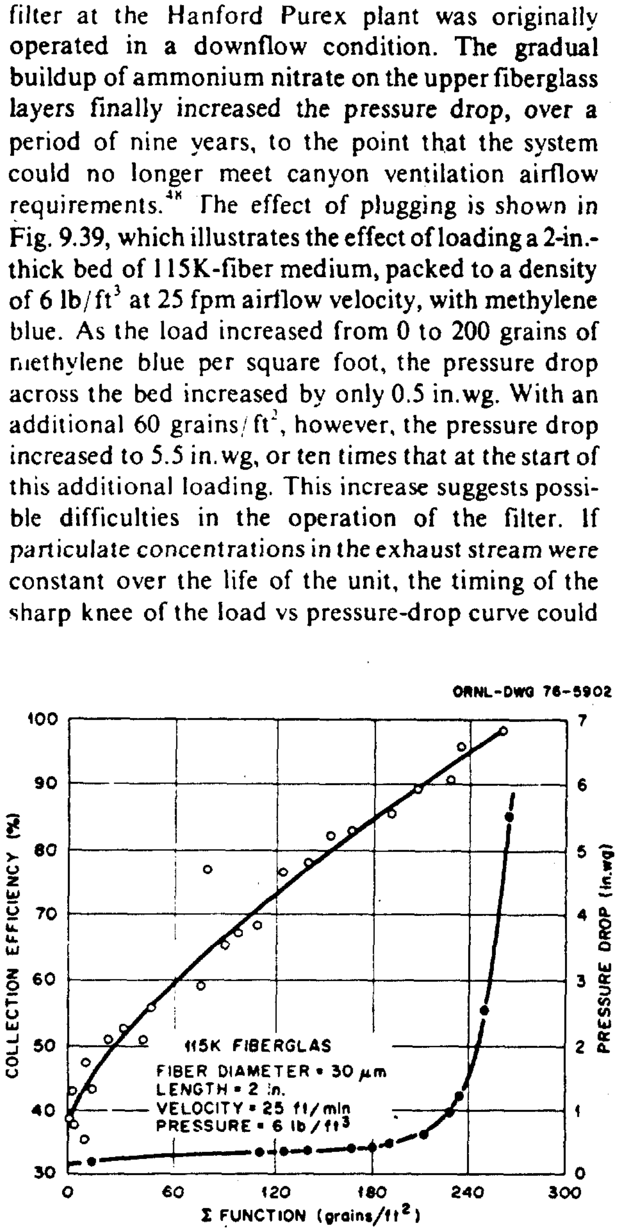

Fig. 9.39. Characteristic collection efficiency and loading curves for DBGF filter.

be predicted. In actual operation, however, particulate concentrations vary substantially from time period to time period, depending on what is occurring at the source. A predetermined pressure drop is generally established as the indicator that a rapid pressure rise is imminent; if the critical loading that determines this guide is located to the right of the knee of the curve, plugging could occur before preplanned preventive action can be taken. If the set point precedes the knee, a small difference in pressure drop can make a large difference in the time interval between when the preventive action is taken and when it is needed.

9.7.5 Disposal of Spent Filters

Because low maintenance requirements are characteristic of large DBGF filters, little consideration was given to the disposal of spent media in early DBGF filter designs. In small units, the entire unit, including container, can be replaced, and the spent unit can be disposed of as solid waste. For large units, as with sand filters, it was considered sufficient that the inlet and exit ducts of the filter could be sealed and the contaminated media left in place. Present requirements for solid-waste handling, though clouded, may rule out such in-place disposal. If new requirements indicate that alpha-bearing material, such as DBGF filter media, must be sealed and safely removed to a site yet to be designated for permanent storage, it may be necessary to design future DBGF filters so that trays or media can be replaced. Media replaceability should not prove too difficult if it is considered in the original filter design; however, tray-removal capability adds substantially to capital costs. Tray-removal capability requires an alternate airflow path during the change-out operation (this can be provided with proper segmentation and the provision of isolation valves), the ability to decontaminate or shield the tray being removed, and an alpha-sealed, and probably remote, handling system. The flexibility gained by the ability to replace trays and media may be advantageous, however, because exact knowledge of future exhaust-air particulate loadings, after the filter goes into operation, is lacking and difficult to estimate before startup.

9.8 REACTOR ENGINEERED-SAFETY-FEATURE AIR CLEANING SYSTEMS

9.8.1 Introduction

Probably in no other field of human endeavor have such extensive, careful, and costly efforts been taken to prevent the occurrence of a major accident as those that have been taken in the design of nuclear reactors. As a result of these efforts, the likelihood of a major accident is considered to be extremely remote.[49] No matter how remote the possibility, however, such accidents must be planned for, and ESF systems must be provided to mitigate the possible consequences. Major ESF systems include the containment postaccident air cleaning system and the control room protection air cleaning system, both of which must be designed to survive the structural and environmental effects of the worst combination of core disruptive accident and natural phenomenon (e.g., earthquake) that can be reasonably postulated for the reactor and yet remain operable during, or be capable of startup and operation following, that incident. Other ESF air cleaning systems include those serving ESF equipment areas and fuel storage areas of the plant. These latter systems are remote from the reactor and would be subjected to a lesser DBA; on the other hand, they must be capable of withstanding a safe shutdown earthquake (SSE), a tornado, or other natural phenomena postulated for the site.

9.8.2 Reactor Containment

Requirements of the containment postaccident air cleaning system depend, in large measure, upon the type of containment employed.[50] There are five basic types of reactor containment: single-pressure containment, double-pressure containment, pressure containment with shield building, vented confinement, and containment/confinement.

In pressure containment (Fig. 9.40), the reactor vessel head space (or head space vault) and reactor bay are enclosed by a large (2×10^6 ft^3 or larger volume), ASME Code-constructed,[51] leaktight (0.1 vol/24-hr maximum permissible leak), steel or steel and concrete vessel designed to withstand the maximum temperatures and pressures developed in the DBA and SSE. A recirculating air cleaning system is provided to minimize the airborne radioactive material that escapes from the pressure containment. Pressure containment with internal recirculating (or kidney) air cleaning facilities was used for several early pressurized-water reactors (PWR) and has been proposed for liquid-metal fast breeder reactors (LMFBR). Because of the extremely severe postaccident service environment (temperatures to 275° F; pressures to as high as 65 psia over the 1- to 10-sec period following a core disruptive accident; relative humidity of 100%; air densities of two to three times normal; and, if containment sprays are used to reduce pressure, sensible moisture in a heavy-rain condition in a PWR), the possible low reliability of filters and adsorbers under this environment, and the inability to repair or replace air cleaning system components following an accident, the internal recirculating or kidney system concept has apparently been abandoned in modern power plant practice, at least for light water reactors (LWR).

An alternative to the internal kidney system is the external recirculating system shown in Fig. 9.41. In this design, air cleaning components are located in pits outside of the containment structure. Isolation dampers in the ducts leading from and to the containment structure permit isolation of the air cleaning system components until the initial pressure transient has passed and pressure across the system

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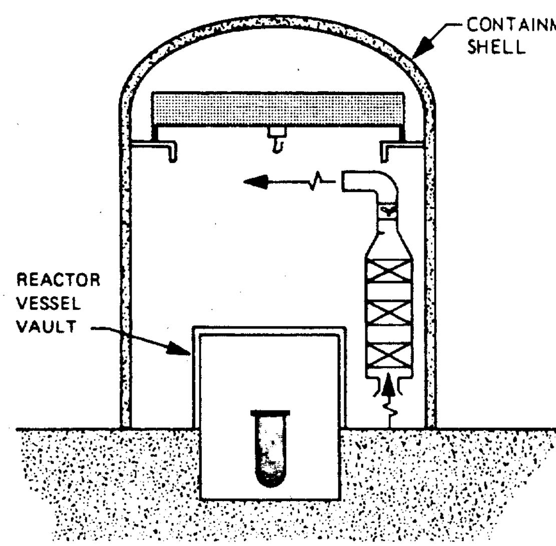

Fig. 9.40. Pressure containment with internal recirculating or kidney ESF postaccident air cleaning system.

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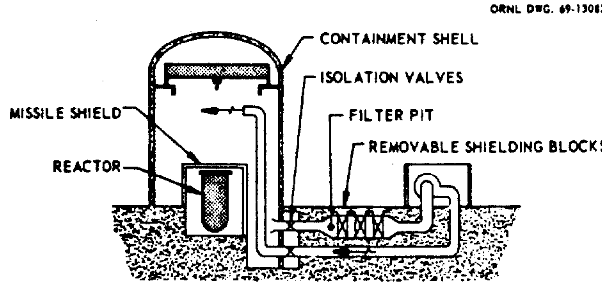

Fig. 9.41. Pressure containment with external recirculating postaccident air cleaning system. In this concept, note capability to repair or replace air cleaning components after an accident.

can be equalized. System components are protected from missiles in the containment, and, with redundant systems, can be repaired or replaced remotely (Sect. 9.2) if necessary. Bypass dampers can be provided to permit operation of the system in the once-through mode for purging the containment. This concept, first proposed in the earlier edition of this handbook,[52] has been considered for power reactors.[51]

Double containment (Fig. 9.42) has been proposed for the LMFBR.[54] In this concept, a pressure containment similar to that discussed above surrounds an inner ASME Code-constructed pressure containment surrounding only the reactor vessel head space. The inner vessel, which must be removable to permit access to the reactor core, has a permissible leak rate of 1 vol per 24 hr but is designed to withstand the maximum pressures and temperatures of a DBA. Kidney-type ESF containment postaccident air cleaning facilities are provided in the outer containment space. Since these facilities "see" only the radioactive material that leaks from the inner containment, and most of the particulate matter emitted in a core disruptive accident would settle or plate out in the inner containment, the loading and environmental conditions to which they are subjected are substantially less than in the case of single containment.

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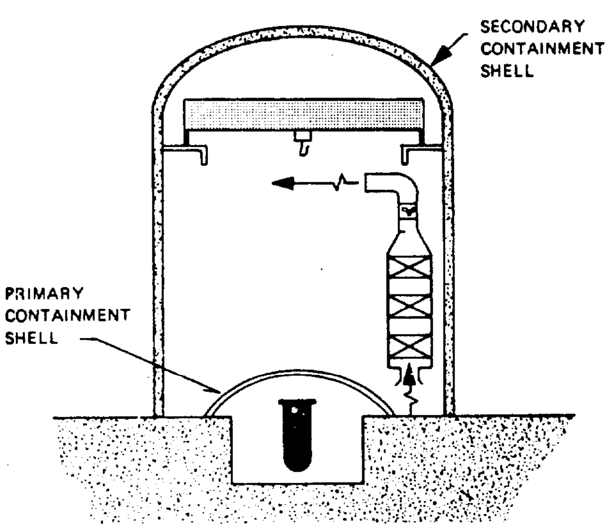

Fig. 9.42. Double containment as proposed for a commercial scale LMFBR. Both containments designed to ASME Code, primary containment shell removable for access to reactor vessel head space. Internal recirculating (kidney) postaccident air cleaning system, no provision for postaccident air cleaning in primary.

Pressure containment with shield building (Fig. 9.43) has been employed in most recent PWRs and in some recent boiling-water reactors (BWR). In this concept, an annular shield building of essentially conventional construction surrounds the pressure containment structure. Any leakage from the primary containment is to the shield space. ESF air cleaning facilities are provided in or adjacent to the shield space. These may be once-through, discharging to the atmosphere, once-through and discharging back to the primary containment (pump-back), or recirculating within the shield space. In most cases, shield space is maintained at a lower pressure than either the primary containment or the atmosphere. Shield-building ESF air cleaning facilities are small (4000- to 6000-cfm installed capacity in the basic system, with 100% redundancy) compared with in-containment kidney systems (as large as 100,000-cfm installed capacity in the basic system, usually with 100% redundancy; a 200,000-cfm ESF kidney system with 100% redundancy was proposed for the LMFBR). As the components are protected from the severe postaccident environment of the primary containment, shield-building systems are obviously much more reliable. A variant of the shield-building concept is the penetration vault that has been used in some reactors. In this design (Fig. 9.44), the shield volume surrounds only the area of the containment structure at which steam lines, piping, electrical conduits, and other penetrations occur.

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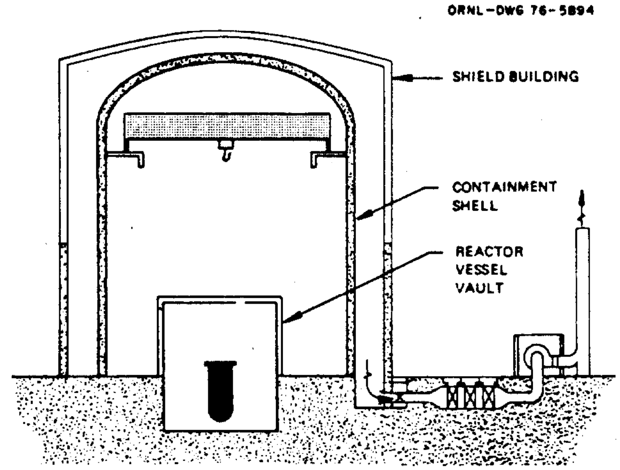

Fig. 9.43. Pressure containment with shield building. Once-through ESF air cleaning system vents shield space to remove contaminants leaked to shield space from containment. External air cleaning facility permits repair or replacement of components following accident.

Vented confinement (Fig. 9.45) is employed in ERDA production reactors and most research reactors. In this design, the reactor vessel head space (or head space vault) and reactor bay are enclosed in a low-leakage building of special, but essentially conventional design.[55] The containment structure is not an ASME Code vessel. ESF air cleaning facilities may be either recirculating, as in the Savannah River reactors, or once-through, discharging to the atmosphere through a high stack (elevated release may reduce offsite doses by an order of magnitude or more, as compared with ground-level release). The confinement building is maintained at negative pressure relative to ambient by means of the exhaust system. In most ERDA and research reactors, the same set of air cleaning facilities serves both the normal operational and postaccident functions. If vented confinement should be used for commercial reactors, it is likely that separate ESF and normal operational systems would be required. The systems are very large (for example, a 128,000-cfm basic-system installed capacity, plus 25% redundancy, in the Savannah River reactors).

Containment/confinement (Fig. 9.46) is employed in most BWRs and is one of the concepts proposed for commercial scale LMFBRs. The reactor vessel, or reactor vessel head space, is enclosed in an ASME Code-constructed containment vessel which, in turn, is surrounded by a confinement building similar to that used for vented confinement. Unlike vented confinement, air cleaning system components are not exposed to the severe postaccident environment of a DBA and are required to remove only the small quantity of material that leaks from the containment vessel or around containment penetrations. Therefore, ESF air cleaning facilities are small, ranging from as low as 4000-cfm basic-system airflow to as much as 16,000 cfm for BWR standby gas treatment systems (SGTS), depending on the size of the confinement building. In all cases, 100% redundancy of ESF air cleaning facilities is required. A basic-system airflow of 15,000 cfm has been proposed for a 1000-MW(e) LMFBR employing the containment/confinement design.[54]

If air cleaning equipment is located high in the containment or confinement building, as has been done in some reactors to conserve space on the reactor or fuel-loading floor,[56] protection against extreme shaking in the event of an earthquake is needed (the amplification of ground-level earthquake

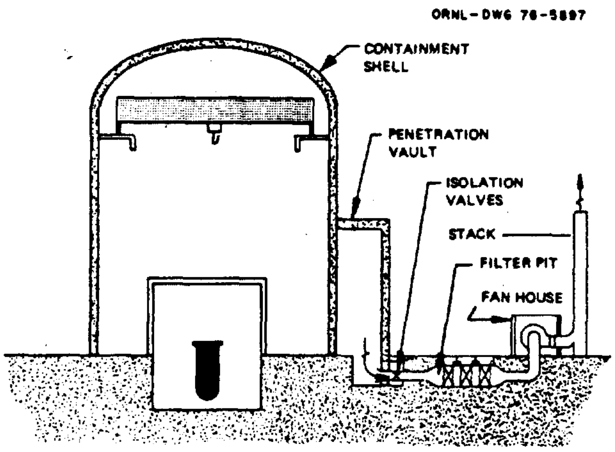

Fig. 9.44. Pressure containment with vented penetration vault.

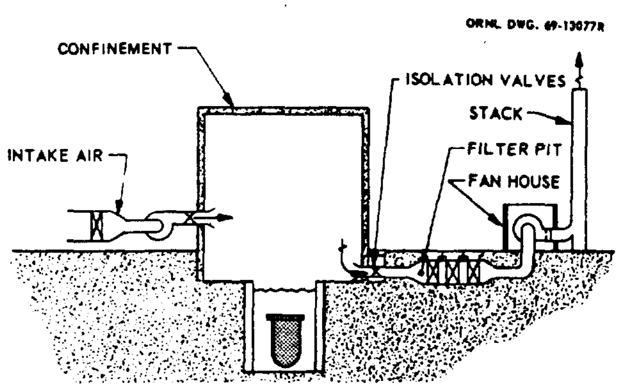

Fig. 9.45. Vented confinement as used in production and research reactors. Once-through air cleaning facilities are on-line at all times during both normal and reactor upset conditions.

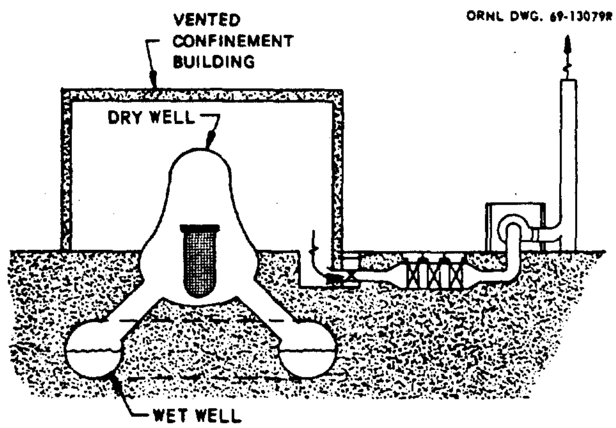

Fig. 9.46. Containment/confinement for BWR with once-through, external-standby gas-treatment system. In event of accident, steam and gases released in dry well expand into wet well where they come in contact with water to reduce pressure and capture some particulate matter and iodine.

acceleration may be as great as 30 to 150, depending on the height of the equipment above ground level).[57]

In all containment concepts, non-ESF air cleaning facilities are usually provided in the containment or confinement building for air cleaning under normal operating, maintenance, or shutdown conditions, and for containment purge. Non-ESF systems are generally much smaller than in-containment postaccident air cleaning systems and are not required to be redundant. In commercial power reactors non-ESF systems are independent of the ESF systems and must be shut down in the event of an accident. Although non-ESF systems do not have to meet the postaccident and earthquake survival requirements of the ESF system, if located in areas where ESF facilities of any type exist, they must be at least designed to resist falling or tearing loose during a core disruptive accident or SSE.

9.8.3 Light Water Reactors

Guidelines for the design of light water reactor ESF air cleaning facilities are given in Regulatory Guide 1.52,[58] which recommends a sequence of air cleaning components consisting of demister, prefilter, HEPA filter, adsorber, and final HEPA-filter stage. A heater is also recommended upstream of the adsorbers to maintain the relative humidity of the air entering the adsorbers at approximately 70% following a loss-of-coolant accident (LOCA). Because radioiodine is the contaminant of major concern in the event of a light water reactor LOCA, the need for two stages of HEPA filters is often questioned, particularly in that prefilters are also required upstream of the first-stage HEPA filters. The first-stage HEPA filters have two functions: (1) protection of the adsorbers from particulates which could "blind" the adsorbent granules, and (2) holdup of iodine-bearing particles. Without the first-stage HEPA filters, these particles could penetrate the adsorber beds and be caught on the downstream HEPA filters, and the iodine adsorbed on them [which accounts for 5% of the postulated iodine load (Sect. 3.4)] would desorb to the air being discharged from the system. The second-stage HEPA filters prevent the loss of iodine-bearing adsorbent fines and also provide backup protection in the event of failure of or damage to the first-stage HEPA filters.

Components of the ESF air cleaning system must be designed, constructed, tested, and maintained to ensure effective and reliable operation when subjected to the postulated environment and service conditions of the DBA. The least-stringent postaccident environment and service conditions would be encountered in the confinement building of a containment/confinement system or in the shield building of a pressure-containment/shield-building system. Although the ESF air cleaning facilities would have to withstand the SSE and humidity of 100%, pressure and temperature transients would be nil, and particulate concentrations and radioactivity levels would be relatively low, compared with vented-containment or pressure-containment systems. Other conditions that have to be considered are pressure transients due to a design basis tornado or to an inadvertently opened or closed damper and shock, vibration, physical displacement resulting from a postulated simultaneous SSE.

Simple vented confinement, because there is no inner containment, is subject to much more stringent postaccident service conditions than the containment/confinement or pressure-containment/shield-building designs. Postaccident service conditions may include radiation levels in air cleaning components of 10^7 to 10^8 rads, temperatures as high as 275°F, and pressures of 2 to 3 psi above atmospheric, in addition to large volumes of condensing steam and, perhaps, sensible moisture. In addition, the system must be designed to withstand the design basis earthquake and tornado. The most severe postaccident conditions would be encountered in a pressure containment with an ESF kidney air cleaning facility. In addition to high radiation levels (10^7 to 10^8 rads), high temperatures (up to 275°F), and large volumes of condensing steam and sensible moisture, ducts and equipment housings may be subjected to high collapsing pressures, as great as 40 to 45 psig during the first few minutes following the core disruption due to the lag of pressure rise in the duct relative to pressure rise in the containment, unless pressure-relief dampers are provided. Fans and motors are required to operate at very high temperatures in saturated air and in air densities of 2 to 3 atm. If chemical sprays are discharged in the containment (to reduce pressure and react with airborne iodine), corrosion of metal parts and chemical attack of filter and adsorber media may also take place.

In all reactor postaccident situations, fission-product-decay heating of carbon in the adsorbers must be considered. With insufficient provision for cooling in the event of main-fan failure, heating of the carbon may result in desorption of the already trapped radioiodine (which would constitute failure of the system) or of the impregnants on which radioiodine trapping depends, or even in ignition of the carbon. Tests have shown that deluge water sprays, often provided for extinguishing carbon fires, are of limited value;[59] in addition, the water washes out both the impregnant and any trapped radioiodine,[60] thus causing further loss of iodine containment and creating a substantial liquid waste problem.

Demisters are required in all systems because of high sensible moisture and possible steam loadings which can plug HEPA filters and degrade the effectiveness of activated carbons for organic iodine compounds. Demisters require adequate drains to carry the collected water to the liquid waste system. If drains are not properly designed and maintained, a bypass of the HEPA filters and adsorbers may be created (through the drain system), which would result in failure or degradation of the air cleaning function. Controls, instruments, sensing and air lines, electrical equipment, and electrical wiring serving the air cleaning system must also be designed to withstand the postulated postaccident environment and conditions without failure. Redundant-unit ductwork and equipment must be geographically isolated, shielded, or installed in individual vaults to protect against single failure from missiles resulting from burst piping or failed equipment and from falling pipes, equipment, and ducts. Redundant units are always required to provide backup air cleaning capacity in the event of on-line unit failure. Provision for remote maintenance, though rarely considered, is desirable to permit the reactivation of failed units or the replacement of damaged or failed components.

9.8.4 High-Temperature Gas-Cooled Reactors

Single pressure containment has been proposed for the commercial high-temperature gas-cooled reactor (HTGR).[61] However, because of the low specific heat of the gas and certain features of the concrete reinforced pressure vessel employed, the postaccident containment environment and service conditions will not be as severe as in the LWR single containment. Although temperature and pressure may reach 700° F and 40 psig, respectively, the duration of these transients will be brief, and startup of the ESF air cleaning facilities can be delayed until the worst of their adverse effects have passed. A typical 1000-MW(e) HTGR employs a recirculating containment postaccident air cleanup system consisting of four 18,000-cfm (installed capacity) units located 90° apart within the containment structure.[62] The basic system installed capacity is 36,000 cfm, with 100% redundancy. During normal and maintenance operations, the containment is held at a slight negative pressure by a 20,000-cfm combination recirculating and once-through purge and containment cooling system operating in a "feed and bleed" mode. If an accident occurs, this system is shut down, and the ESF units are brought on line following a 2-sec to 15-min delay to permit decay of initially high postaccident temperature and pressure. Although there are no regulatory guides governing high-temperature gas-cooled reactor ESF air cleaning facilities, it is likely that an air cleaning unit configuration similar to that recommended in Regulatory Guide 1.52[58] for LWRs would be advised, that is, a train consisting of demisters, prefilters, first-stage HEPA filters, adsorbers, and second-stage HEPA filters. Although the reactor coolant is helium gas, free water or steam could be present in the containment due to the rupture of feedwater or secondary-coolant piping; therefore, demisters would be required. All requirements of the LWR for protection of ESF air cleaning facilities from tornados, earthquakes, pressure transients, missiles, and other postaccident environmental and service conditions would apply equally to the HTGR.

9.8.5 Liquid-Metal Fast-Breeder Reactors

Two features influence the design of ESF air cleaning facilities for LMFBRs. First, the large plutonium inventory of the fuel makes inhalation of plutonium-bearing aerosols the major concern rather than inhalation of radioiodine, as is the case in LWRs and HTGRs. Second, there is potential for a sodium fire which can produce large quantities of thick, viscous fumes (sodium hydroxide and oxides) that can rapidly plug many air cleaning devices, especially HEPA filters. Although one may not normally associate water with an LMFBR, burning sodium in contact with concrete can release substantial quantities of water (hydration from the concrete), creating a relative humidity in the contained space approaching 100%.

Three containment concepts have been considered for the commercial-scale [1000-MW(e)] LMFBR: single containment, double containment, and containment/confinement. For the single-containment case, a 200,000-cfm basic-system installed capacity (plus 100% redundancy) postaccident air cleanup system was proposed,[54] consisting of low-efficiency (~50% ASHRAE dust spot) prefilters and one bank of HEPA filters. Radioiodine adsorbers were not considered necessary because of the ready reaction of iodine with sodium and sodium fumes, and because the large installed capacity was designed to accommodate the large quantities of sodium fumes that would evolve.[63] As with the PWR, the severe postaccident environment in the containment space makes serious consideration of this type of system unlikely. Postaccident environmental conditions include a gas temperature of 300°F, maximum containment pressure of 10 psig, maximum RH of 100%, and 0.7 g/cm^3 particulate concentration. In addition, the probable poor reliability of HEPA and other fiberglass-medium filters in a caustic environment and the probable poor performance of any filter against very sticky particles, as would exist with moist sodium fumes, would further legislate against this choice of system.

Double containment with ESF air cleaning facilities in the secondary containment space has a much greater chance of successful and reliable operation under accident conditions. A much smaller system (72,000- to 75,000-cfm basic-system installed capacity, plus 100% redundancy), again consisting of prefilters and HEPA filters only, is required since the secondary containment "sees" only leakage from the primary (the primary containment vessel is assumed to leak a maximum of 1 vol per 24 hr), and the possibility of a sodium fire in the secondary containment space is eliminated by inerting that space with nitrogen. Again, radioiodine is contained in the primary containment space due to the ready reaction of iodine with sodium and sodium fume and the plate-out and settling of the fume particles within the primary space. Although proposed for a 1000-MW(e) plant,[64] double containment has the drawbacks of high temperature (up to 300°F over a 60-hr period) and humidity (up to 100% RH) in the secondary containment space, which may make for low long-term reliability of filters and the inability to replace or repair components following an accident. This inability can be offset by providing an external recirculating loop, as shown in Fig. 9.41.

Containment/confinement with ESF air cleaning facilities in the confinement space appears to be a promising system for commercial LMFBRs. The primary containment is identical to that proposed for the double-containment case and, as in the double-containment case, the ESF air cleaning facilities "see" only the material that leaks from the primary containment. The confinement building is continuously vented by a non-ESF purge and cooling system during normal and maintenance operations and by the ESF system in the event of an accident. Therefore, the temperature in the confinement space is no more than slightly above ambient (110°F) unless there is a sodium fire, in which case the temperature might reach 200 to 300°F during the period of the fire. A sodium fire in the reactor bay is a major consideration of this concept, and a very large prefilter stage would be required to accommodate the fume arising from a burning 1000-ft^2 sodium spill. Furthermore, because the fire might release water of hydration from the concrete (the water content of concrete averages 9 lb/ft^3),[65] the fume would be sticky and would tend to clog air cleaning devices. Although airflow requirements of the system are small (15,000 cfm), the basic-system installed capacity of the prefilter and the first-stage HEPA filter stages would have to be about 480,000 cfm to accommodate the large volume of fume resulting from a sodium fire in the confinement space.[63] Because venting would continuously remove sodium fume in the containment atmosphere, no reaction between iodine and sodium in the secondary space can be assumed, and iodine adsorbers would be required. Extrapolating recommendations from Regulatory Guide 1.52,[58] a second stage of HEPA filters is necessary. The installed capacity of the adsorbers and second-stage HEPA filters would be 15,000 cfm, and 100% redundancy of all stages, including the very large prefilter and first-stage HEPA filter stages, would be necessary. An alternative to the very large (960,000 cfm total installed capacity) prefilter and first-stage HEPA filter stages might be a 480,000-cfm-capacity sand filter. As noted in Sect. 9.6, sand filters can be designed to approach the efficiency of a HEPA filter; therefore, first-stage HEPA filters could probably be eliminated. The sand filter has the advantages of providing an excellent heat sink and shock snubber, and because redundancy would not be required, might be cost-competitive with the large prefilter and HEPA-filter stages.

9.8.6 Control Room Protection Air Cleaning Systems

Control room protection air cleaning systems are ESF systems that must meet the requirements of Regulatory Guide 1.52.[58] Unless the internal components (filters, adsorbers) are located at the wall penetration of or within the controlled space, the system is generally of forced-flow configuration and operates in a recirculating mode. In most cases.

the air cleaning facilities are external to the control room (controlled space). Positive pressure in the housings and ducts downstream of the fan minimizes inleakage of potentially contaminated air from building spaces surrounding the control room. Most systems have provisions for makeup air from outside of the building, with isolation dampers to cut off makeup airflow if necessary. The proposed control room for a 1000-MW(e) HTGR has two makeup air ducts that can draw air from two geographically isolated areas outside of the reactor site boundary, permitting a constant supply of makeup air even in the event of an accident.[61] The location of control room protection system components within the control room has the advantage of maintainability under accident conditions; however, it also has the disadvantage that maintenance operations must be conducted within the control room, an activity that may be untenable to some operators.

The component train of a control room protection system should include prefilter, HEPA filter, adsorber, and second-stage HEPA filter. Prefilters are recommended even though the system recirculates very clean air, because the lint generated by personnel moving about in occupied spaces can bridge the pleats of HEPA filters, reducing their capacity. Makeup ducts should be fitted with prefilters and one stage of HEPA filters, and should have a high-quality isolation damper to cut off the makeup air in the event of a release of toxic or debilitating industrial gases (e.g., chlorine) in the area of the makeup intake. Redundancy is necessary and is usually provided by two or more totally independent and geographically isolated systems, each capable of furnishing the needs of the control room.

9.9 FUEL REPROCESSING PLANT AIR CLEANING

9.9.1 Introduction

The requirements for air cleaning in fuel reprocessing facilities differ greatly from those for a power reactor. Basically, the difference stems from the fact that day-to-day operations in a reactor are clean, whereas day-to-day operations in a reprocessing facility are inherently dirty. In a reactor, air cleaning facilities are designed to accommodate a large radioactivity release under accident condition, whereas the fuel reprocessing facility must accommodate the potential for smaller, but still substantial, releases under normal operating conditions. Effluent air and gases from reprocessing operations are likely to contain substantial quantities of acid or caustic that must be removed before getting to final air cleaning facilities. In a reactor there are several lines of containment for fissile material and fission products, including the fuel cladding, the reactor vessel, and the containment structures; in the fuel reprocessing plant these lines are all lacking, and, although the fuel is handled one rod at a time, the cladding is purposely removed to release the fissile and radioactive materials (under controlled conditions) for processing. In a reactor, fuel is always in an essentially static condition except when it is being loaded into or unloaded from the reactor vessel or being moved to or from the storage pool. On the other hand, in a reprocessing plant, the fuel and its subsequent byproducts are constantly in an active condition, being chopped, dissolved, leached, or otherwise acted upon. The potential for a release of radioactive material or nuclear criticality incident in the fuel reprocessing facility, therefore, is an ever-present condition.

The requirements for the design, construction, testing, and maintainability of air cleaning systems for the fuel reprocessing and radiochemical facility differ little from those for reactors. That is, generally the same components (demisters, prefilters, HEPA filters, ducts, fans, dampers, and housings) are employed, and differences are in the details of application rather than in the basic principles of application. Basically, the design and installation of air cleaning components and equipment should follow the guides in this handbook. Other guides and standards of particular interest in fuel reprocessing and radiochemical applications include:

Regulatory Guide 3.12, *General Design Guide for Ventilation Systems of Plutonium Processing and Fuel Fabrication Plants.*

Regulatory Guide 3.14, *Seismic Design Classification for Plutonium Processing and Fuel Fabrication Plants.*

Regulatory Guide 3.18, *Confinement Barriers and Systems for Fuel Reprocessing Plants.*

Regulatory Guide 3.20, *Process Offgas Systems for Fuel Reprocessing Plants.*

Regulatory Guide 3.24, *Guidance on the License Application, Siting, Design, and Plant Protection for an Independent Spent Fuel Storage Installation.*

Code of Federal Regulations, Title 10, Part 20, *Standards for Protection Against Radiation.*

Code of Federal Regulations, Title 10, Part 50, Appendix P, *General Design Criteria for Fuel Reprocessing Plants.*

ANSI N101.3, *Guide to Principal Design Criteria for Nuclear Fuel Reprocessing Facilities.*

ANSI N303, *General Requirements for Control of Gaseous Effluents Containing Radioactive Material at Nuclear Fuel Reprocessing Facilities.*

Air and gas cleaning systems fall in one or the other of two broad categories, ventilation or off-gas. Ventilation air cleaning systems are often very large, as much as 250,000 to 300,000 cfm, although the trend appears to be toward smaller once-through systems. These systems are fed from a number of small branch lines, each of which is generally equipped with at least a HEPA filter at the duct entrance. The central exhaust air cleaning system generally consists of a bank of prefilters and a bank of HEPA filters, although a DBGF prefilter followed by one stage of HEPA filter, or a sand filter alone with no HEPA filters at the central-exhaust plenum, is used in some ERDA installations. Normal off-gas systems are generally small, seldom more than 1000-cfm and often 100-cfm airflow. Gases evolved in chemical operations are pretreated by condensation, scrubbing, or other chemical engineering techniques to remove acids, caustics, excess moisture, and other materials that could harm filters or adsorbents. In some plants, off-gas exhausts directly to a high stack; in others it is discharged to the central building-exhaust air cleaning system to provide series redundancy of the final filtration step.

9.9.2 Light Water Reactor Spent Fuel Reprocessing

The Barnwell Nuclear Fuel Plant located near Barnwell and Aiken, South Carolina, represents the present-day design of equipment and systems and the current state-of-the-art techniques for ensuring that any release of radioactive material to the environment, under both normal and system upset conditions, is maintained at levels that meet current ALARA criteria.[66] The Barnwell plant has not gone into operation as of June 1976.

Air in operating cells and galleries is maintained at less than atmospheric pressure so it will flow from areas of no contamination toward areas of increasing contamination potential. Exhaust air from sources of potential contamination is passed through a duct-entrance filter near the source, then to the main building or laboratory ventilation system. Air pressure in occupied areas and aisles is maintained at slightly higher than atmospheric. All ventilation air is exhausted through one of two ventilation air cleaning systems having a single bank of HEPA filters, then to a 100-m stack. Most first-stage duct-entrance HEPA filters will be changed remotely, but radioactivity levels at certain low-activity cells and at the central building-exhaust plenum are expected to be low enough to permit contact maintenance. The quantities of radioisotopes in the ventilation air streams will be relatively insignificant under normal operating conditions. Ventilation air for fuel receiving and storage areas is independently supplied and exhausted directly to the atmosphere or recirculated (through roughing filters only) without additional treatment since no contamination is expected at these points.

Off-gas from the shear and dissolver is passed through a dust screen to remove large particles, through a condenser to remove most of the water and soluble contaminants, through a mercuric nitrate–nitric acid scrubber to remove noncondensible iodine, through a vapor–liquid phase separator, and through an absorption column where nitrogen and nitrogen oxides will be oxidized with air and absorbed in water. This dissolver off-gas stream is then discharged to the main process vessel off-gas (VOG) system. The nitric acid and iodine content of gases entering the VOG system should be quite low; however, an additional iodine scrubber is provided. The VOG system, consisting of a condenser, a vapor–liquid phase separator, a second iodine scrubber, and a gas heater, then exhausts to the stack through an air cleaning unit having HEPA filters (two stages) and zeolite-filled adsorbers. No provision is made for trapping or removing the noble gases. It has been proposed that the VOG stream, after pretreatment and one stage of HEPA filters and adsorbers, be discharged to the building-exhaust air cleaning system. For reasons given earlier, a second stage of HEPA filters should be provided downstream of the adsorbers.

9.9.3 LMFBR Spent Fuel Reprocessing

Plutonium produced in the operation of LMFBRs must be separated from other components of the spent fuel, fabricated into new fuel assemblies, and then returned to the reactor in as short a time as practical in order to benefit from the LMFBR's more efficient use of uranium. Air and gas cleaning techniques employed in reprocessing fuel from LWRs (Sect. 9.9.1) are similar in many ways to those which will be used for processing LMFBR fuel. However, there are special problems that must be dealt with, including the handling of thermally hot, sodium-contaminated fuel assemblies, the design, construction, and operation of very low leakage cells for reprocessing activities, the recirculation and cleanup of argon or nitrogen cell atmospheres, and the application of the near-zero release concept (Sect. 9.9.4) to provide a high degree of containment of not only plutonium, uranium, and iodine, but also tritium, krypton, xenon, and possibly ruthenium.

One concept of an air–gas cleaning system for an LMFBR fuel storage and reprocessing facility utilizes at least three stages of HEPA filtration, a 300-m off-gas stack, a sand filter for natural or DBA emergency protection, iodine removal, and provisions for the future retention of tritium, krypton, xenon, and ruthenium. Under this concept, cells are designed for very low air inleakage, on the order of 0.01 cfm/cell under sealed test conditions. This and other Zone I (Sect. 2.2.1) exhaust rates are limited to a total of 100 cfm. Recirculation of the cell inert atmosphere (nitrogen) is a requirement. In cells where sodium is present, both the oxygen and moisture content must be controlled to a maximum of 50 ppm by volume. The regulation of pressure and temperature is necessary, and redundant air moving and air cleaning equipment must be provided. The removal of sodium fumes and organic vapors is also necessary in recirculating streams where these contaminants are likely to occur. Dual silver-zeolite adsorbers provide iodine retention, with provisions being made for obtaining higher retention factors for iodine (10^7–10^9) by combining nitric acid scrubbing (Iodox process, under development) and solid adsorbents. Problem areas associated with LMFBR fuel reprocessing, including disassembly, fuel rod shearing voloxidation, dissolution, and solvent extraction, are under investigation, particularly in the areas of retention of the volatile fission products–tritium, Kr-85, I-129, and I-131. It appears that tritium can be removed by exposing the fuel to high temperatures (voloxidation); the released tritium is condensed and stored as tritiated water. Krypton can be removed by fluorocarbon selective absorption. Iodine removal is accomplished by acid scrubbing followed by adsorption on silver-zeolite. Plutonium, uranium, and other radioactive particulates are controllable by existing filtration technology, as previously discussed in this handbook.

Key concepts for LMFBR spent fuel reprocessing facility design include the following:

- Confine radioactive gases and particulates within low-leakage process equipment enclosures by means of HEPA filters. Exhaust and recirculated gas streams from these enclosures should be filtered as close to the contaminant source as practicable. The need for radioactive gas retention facilities downstream from the HEPA filters is yet to be determined.

- Limit the total air–gas exhaust from the cells and other Zone I areas to as low as practical, possibly a maximum of 100 cfm. This demands that the hot-cell work areas have very low air inleakage.

- Perform cleaning operations on the cell exhaust stream as necessary to result in a near-zero release level. Cleaning processes should include the removal and retention of essentially all of the plutonium, uranium, iodine, krypton, xenon, tritium, and ruthenium.

- All plutonium-contaminated streams should undergo at least three stages of HEPA filtration before discharge to the plant atmosphere.

- A deep-bed sand filter or equivalent should be provided for fire, shock, and explosion protection, followed by a HEPA filter stage. The final HEPA filter bank must be operable under all possible DBA, earthquake, tornado, and other postulated disaster and emergency conditions.

- Where sodium is encountered, the use of either a nitrogen or argon cell atmosphere is necessary. The cell atmosphere must be recirculated through HEPA filters and gas purifiers for particulate removal, maintenance of gas purity, and cell temperature and pressure control.

- Provide monitors with alarms, redundant air moving and air cleaning equipment, and central control room operation for maximum reliability.

9.9.4 Near-Zero Release Concept

In the past, radioactive discharges have been limited to quantities that would yield concentrations of radioactive contaminants at site boundaries well below levels set by national and international agencies for continuous intake by the public.[67] The present emphasis is to ensure that releases of radioactive material are, in addition, kept to as low a value as reasonably achievable. It is believed that reductions in effluent activities and volumes to levels approaching near zero can be achieved in future facilities. The near-zero confinement objective can be realized by a reasonable projection of the technology currently in development. Although the related process development work is not complete, it appears that the following retention factors can be attained: iodine, 10^{10}; noble gases and tritium, 10^5; and particulates, 10^{16}.[68]

As LMFBRs (with their higher burnup levels, higher specific power, and the economic incentive to reduce spent-fuel preprocessing decay time) assume their projected role in the power economy of the future, the input level of fission products to reprocessing plants will increase significantly. This higher input level of activity, coupled with possible reductions in the permissible release of activity to the environment, will place very stringent demands on effluent control systems and require advanced processes for the control and removal of the volatile fission products from effluent streams. The current practice of using once-through ventilation for cell enclosures at rates in the 100,000-cfm range is not compatible with the near-zero release concept of activity from the plant. The removal of trace concentrations of tritium, krypton, and iodine from very large air and gas flows is economically infeasible as well as technically unsound.

Key factors in reducing the quantity of radioactivity released to the environment to near zero include a reduction in the volume of effluents, low air inleakage into cells, and avoidance of bypassing of contaminant trapping systems. The practical extent of the treatment of an effluent is determined in large measure by the volume of the effluent to be treated. A large shielded fuel examination facility (the High-Level Fuel Examination Facility at the National Reactor Testing Station, Arco, Idaho) is operating with an air infiltration rate of 0.004 cfm. It is believed that a practical infiltration rate for a 5-tonne/day reprocessing facility, designed for near-zero radioactivity release, is 100 cfm or less. To meet these objectives, a high degree of overall containment must be maintained during all phases of plant life, including routine operation, maintenance, and decommissioning at the end of the plant's useful life.

9.9.5 HTGR Spent Fuel Reprocessing Air Cleaning Systems

Although no HTGR fuel processing plant is yet in the design stage, it is likely that air and gas cleaning facilities for such a plant would be similar in many respects to those of an LWR spent fuel reprocessing plant. Building design and containment philosophy are similar except that Zone III areas of the plant (operating areas and aisles) would probably be maintained at a slight negative pressure relative to the out-of-doors, and galleries and cells would be maintained at progressively lower pressures in order to maintain airflow in the building from areas of low hazard to areas of progressively higher hazard.

The total projected off-gas volume from the head-end processes and dissolver is 380 scfm. The nitrogen oxides in the dissolver off-gas stream are catalytically decomposed to N_2 and H_2O, using ammonia. The head-end and dissolver off-gas streams are then mixed at subatmospheric pressure and compressed. Excessive CO and/or H_2 are removed in a high-temperature oxidizer by conversion to CO_2 and tritiated water. Iodine is removed by adsorption on lead-zeolite and silver-zeolite beds in series. Radon is held up on a molecular-sieve bed for decay to stable lead, and tritiated water vapor is removed by adsorption in a molecular-sieve bed (the tritiated water is fixed in concrete for disposal). The gases are then passed through a HEPA filter, compressed to a pressure in excess of 20 atm, cooled to $-35°$ C, and treated to remove krypton. Krypton is removed by absorption in liquid CO_2, and the decontaminated gases are vented to the main ventilation exhaust system. Krypton is then stripped from the liquid CO_2 by fractional vaporization and desublimization to freeze out the remaining CO_2, after which it is compressed and bottled for indefinite storage. A final system design description for off-gas treatment had not been issued at the time this handbook was published.

9.9.6 Air Cleaning System Costs, Fuel Reprocessing

Comparisons of construction costs of cell ventilation exhaust air cleaning systems for reprocessing plants can be misleading because of the difficulty in establishing valid equivalency bases. The extent of the construction costs included in the figures reported, the type of construction contract, regional cost differentials, differences in the terrain on which the facility is built, and cost escalation are some of the factors that make such comparisons misleading. With these words of caution, a construction cost comparison of fuel reprocessing and radiochemical plant exhaust air cleaning systems is given in Tables 9.6 and 9.7.

Table 9.6. Estimated unit cost (dollars per cfm of installed capacity) of various fuel reprocessing plant exhaust air cleaning systems (based on data in Table 9.7)

Type of system	Number of systems	Cost in 1975 dollars
Sand filter	7	25.76
DBGF filter	2	9.21
DBGF, one HEPA filter	1	16.67
One prefilter, two HEPA filters	3	4.08
Two prefilters, three HEPA filters	2	11.76

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Table 9.7. Construction cost comparison, reprocessing plant cell and building ventilation-exhaust air cleaning systems[a]

Location	Facility No.	Type	Installed capacity (scfm × 10^3)	First cost ($ × 10^6)	Completion date	Unit cost in year of construction ($/cfm)	Unit cost related to 1975 dollars[b] ($/cfm)
Hanford	291-B	Sand	26	0.311	1948	11.96	30.98
Hanford	291-T	Sand	25		1948		
Hanford	291-U	Sand	44		1950		
Hanford	291-S	Sand	40		1951		
SRP[c]	294-F	Sand	115	1.51	1954	13.13	27.70
SRP	294-H	Sand	115	1.25	1955	10.87	22.39
Hanford	291-A-1	DBGF	126	0.556	1955	4.41	9.08
Hanford	291-A-2	DBGF	126	0.671	1965	5.33	9.33
Hanford	291-Ba	1 pre., 2 HEPA	75	0.350[d]	1967	2.33	3.87
Hanford	291-Bb	1 pre., 2 HEPA	75		1967	2.33	3.87
Hanford	291-Bc	1 pre., 2 HEPA	75	0.254	1972	3.39	4.51
SRL[e]	794-A	Sand	74	1.94[f]	1974	26.22	28.84
Morris, Ill.	MFRP	Sand	32	0.400	1974	12.50	13.75
Hanford	291-Bd	2 pre., 3 HEPA	75	0.900	1975	12.00	12.00
SRP	294-1F	Sand	210	5.60	1975	26.67	26.67
Idaho Falls	756	DBGF, HEPA	150	2.50	1976	16.67	16.67
SRP	294-1H	Sand	210	6.30	1976	30.00	30.00
Hanford	291-A-3	2 pre., 3 HEPA	126	1.45	1977	11.51	11.51

[a] Most of the information in this table is based on data from H. A. Lee, *Engineering Study-B Plant, Fifth Filter Cell*, USAEC Report ARH-CD-447, Atlantic Richfield Hanford Co., September 1975.

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